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**OCEAN ENGINEERING**  
**SUMMER LABORATORY 1974**

**Massachusetts Institute of Technology**  
**and**  
**Maine Maritime Academy**

Prepared by Students under the Supervision of  
Professor A. Douglas Carmichael - M.I.T.  
Professor David B. Wyman - M.M.A.



Massachusetts Institute of Technology  
Cambridge, Massachusetts 02139

**Report No. MITSG 75-12**  
**April 15, 1975**

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Report No. MITSG 75-12  
Index No. 75-112-Nos

MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
CAMBRIDGE, MASS. 02139

SEA GRANT PROGRAM

ADMINISTRATIVE STATEMENT

The main purpose of the Ocean Engineering Summer Laboratory is to provide undergraduate students with the opportunity to design, build, and test equipment for the ocean environment. The work of the students described in this final report of 1974 Student Summer Laboratory was conducted jointly by faculty and students of the Massachusetts Institute of Technology and the Maine Maritime Academy.

Of particular significance in this year's report are the student accomplishments in the design and testing of the Submarine robot described in Chapters 1 through 6, the supporting catamaran tender for the submarine robot in Chapter 7 and the cable strumming experiment in Chapter 10.

Ira Dyer  
Director

April 1975

#### ACKNOWLEDGEMENTS

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The participants gratefully acknowledge the willing assistance, encouragement, and expert advice from Lt. Cdr. Herman Kunz, USN (Ret.) and Captain Willard F. Searle, USN (Ret.) of Searle Consultants.

We are all grateful for the tolerance, understanding, and help of the administration, faculty, and staff of the Maine Maritime Academy during the month of July when the Summer Laboratory activity was at its peak.

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Consultants

Herman Kunz

Willard F. Searle

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## SUMMARY

The fourth Ocean Engineering Summer Laboratory has been successfully completed and is reported here. The descriptions of the various projects undertaken by the students are presented as chapters of this report. The first seven chapters provide description of the robot submarine and the catamaran support vehicle which are probably the most ambitious projects undertaken as part of the Ocean Engineering Summer Laboratory. The remaining ten chapters present details of other oceanographic and ocean engineering experiments.

### PROJECT SUMMARIES

<u>No.</u>	<u>Title</u>	<u>Student Participants</u>	<u>Summary</u>
1	The Robot Submarine		The purpose of the submarine is described.
2	The Hull Design	A. G. Sterling D. W. White D. L. Wolk A. B. Zolotas D. Nowak D. S. Hoover	The design and fabrication of the hull, control surfaces and servo systems is presented. The outer skin is fiberglass and aluminum with the critical components placed in watertight cylinders.



<u>No.</u>	<u>Title</u>	<u>Student Participants</u>	<u>Summary</u>
3	Propulsion and Power Supplies	D. Nowak R. J. Wadley C. L. Finkelstein	The robot was powered by a pressure compen- sated lead acid battery and propelled by a two bladed propeller.  Regulated power supplies were provided for the electronic components.
4	The Robot Computer System	L. R. Carley G. R. Carmichael D. K. Christopher G. J. Keller W. E. Mixon J. M. Driear T. J. Teixeira	A mini computer to provide control information was designed and built. Software for the computer was also developed. Systems for providing input to the computer were also developed.
5	The Autopilot and Sensors	C. L. Finkelstein R. A. Longhorn W. E. Mixon J. P. Moussouris	An autopilot and sensors were designed to maintain the attitude and course of the submarine at preset values.
6	Conclusions and Recommendations for the Robot Project		Testing of the robot submarine at Castine is described. Recommendation

<u>No.</u>	<u>Title</u>	<u>Student Participants</u>	<u>Summary</u>
			for improvement to the robot are presented.
7	Catamaran Support Vessel for the Submersible Robot	D. C. Kendall W. T. Sullivan H. E. Wittnebert	A very successful 15' catamaran was designed and built to support the robot. This vessel was used during the robot tests.
8	A Submerged Recording Tide Gauge	J. P. Radochia	A tide gauge which senses water pressure above it and provides a record of the pressure and hence tide height was developed.
9	The Development of and Electromagnetic Flowmeter	L. A. Schneeman	An electromagnetic current meter was designed and built using a 10 Hz driving signal.
10	Cable Strumming Experiments	N. B. Davis S. M. Grumpel S. D. Jessup E. A. Kimball R. W. Matson	Long nylon ropes were stretched across a sandbar and the amplitude and frequency of the cables were recorded as the water velocity varied with tidal conditions.

<u>No.</u>	<u>Title</u>	<u>Student Participants</u>	<u>Summary</u>
11	An Electromagnetic Underwater Communication System	D. White	A transmitter and receiver system was designed to investigate electromagnetic transmission in the ocean.
12	A Savonius Rotor Power Generator	R. J. Schepens R. J. Yak	A power generator was designed, built, and tested.
13	The Floating Breakwater	C. C. Blatchley J. C. Jackson B. C. Amero	A floating breakwater constructed from tractor inner tubes and a reinforced plastic cover was designed and built.
14	A Preliminary Study of Diver Propulsion Using Compressed Air	D. B. Jones	The drag of a fully equipped SCUBA diver was measured. The preliminary designed of a pneumatic propulsion system was completed.
15	An Underwater Power Jack	L. A. Kahn	A Hydraulic Power Task was used as the power source for an underwater jack.

<u>No.</u>	<u>Title</u>	<u>Student Participants</u>	<u>Summary</u>
16	A Manganes Nodule Mining Device	B. G. Hughes L. Q. Sax	A model of a manganese nodule gathering device was designed, built, and tested.
17	Underwater Archeological Work on the "Defence"	B. L. Collins M. G. Haluska P. G. Lenfast D. N. Tothill H. K. Dunning	A detailed survey of the revolutionary wreck was conducted

## PREFACE

The Ocean Engineering Summer Laboratory provides the opportunity to design and build equipment for use in the oceans and then to test that equipment. This is the primary objective of the Laboratory experience.

The seventeen chapters of this report summarize the activities, accomplishments and minor disasters of the various experimental studies which were completed as part of the fourth Ocean Engineering Summer Laboratory. These reports do not, however, convey the whole engineering experience as the joint activities were not mentioned. These joint activities included the diving program and regular evening meeting when engineering films were shown and projects were discussed.

### THE DIVING PROGRAM

About half the students participating in the Summer Laboratory took part in dives described in Chapter 17 of this report. Much of the program was concerned with the survey of the "Defence" but other diving tasks were conducted. The diving and salvage program was supervised by Captain Willard F. Searle, U.S.N. (Ret.) and Lt. Cdr. Herman Kunz, U.S.N. (Ret.) The safety officer for the diving program was Professor Edgar Biggie of the Maine Maritime Academy. The diving program was conducted on every day during the month of July that weather permitted. Student divers who were responsible for other engineering experiments were expected to spend two thirds of their time on their own project and one third on diving. The "Panthalass" was used for the main diving expeditions. She was commanded on alternate days by Professors David B. Wyman and Groves Herrick of the Maine Maritime Academy.

#### OTHER ACTIVITIES

Almost every evening there was an informal meeting at which the various projects were discussed and ocean engineering movies were presented. Distinguished visitors also presented engineering seminars on the problems of deep diving and the clearing of explosives from the Suez Canal. Captain Willard F. Searle kindly organized the selection and the collecting of the movies and also the invitations to the speakers. In addition a one day workshop on Underwater Archeology was held, with participants from the State and local museums.

## 1. THE ROBOT SUBMARINE

The largest and most ambitious project of the 1973-1974 summer laboratory was the design and construction of a small computer controlled robot submarine. The mission of this vehicle was defined as broadly as possible since its major function was to give the participants experience in ocean engineering. Uses of the vehicle would include bottom searches and surveys with camera and/or sonar sensors, oceanographic research and research into methods of navigating and controlling small submersibles.

The basic feature of the design was that the vehicle be small enough to be used without handling equipment. This limited the weight to around 250 lb., giving a vehicle size of approximately 8 feet in length and 15 inches diameter. The power source chosen was an automotive lead-acid battery. In spite of this small size, the calculated range of 14-20 miles at three knots indicates that even such a minimal vehicle can have reasonable performance. A preliminary design sketch of the robot is shown on Figure 1.1.

The hull consists of a free flooded skin with a cylindrical aluminum center section and fiberglass nose and tail. The flotation is provided by 13 PVC tubes ranging from 2 to 6 inches in diameter arranged to provide structural strength and optimum packing density. Three of these tubes house the control and propulsion systems.

From the beginning of the design work it was clear that the vehicle must be entirely self controlled. Sufficient acoustic bandwidth exists to telemeter control information to the submarine from a nearby

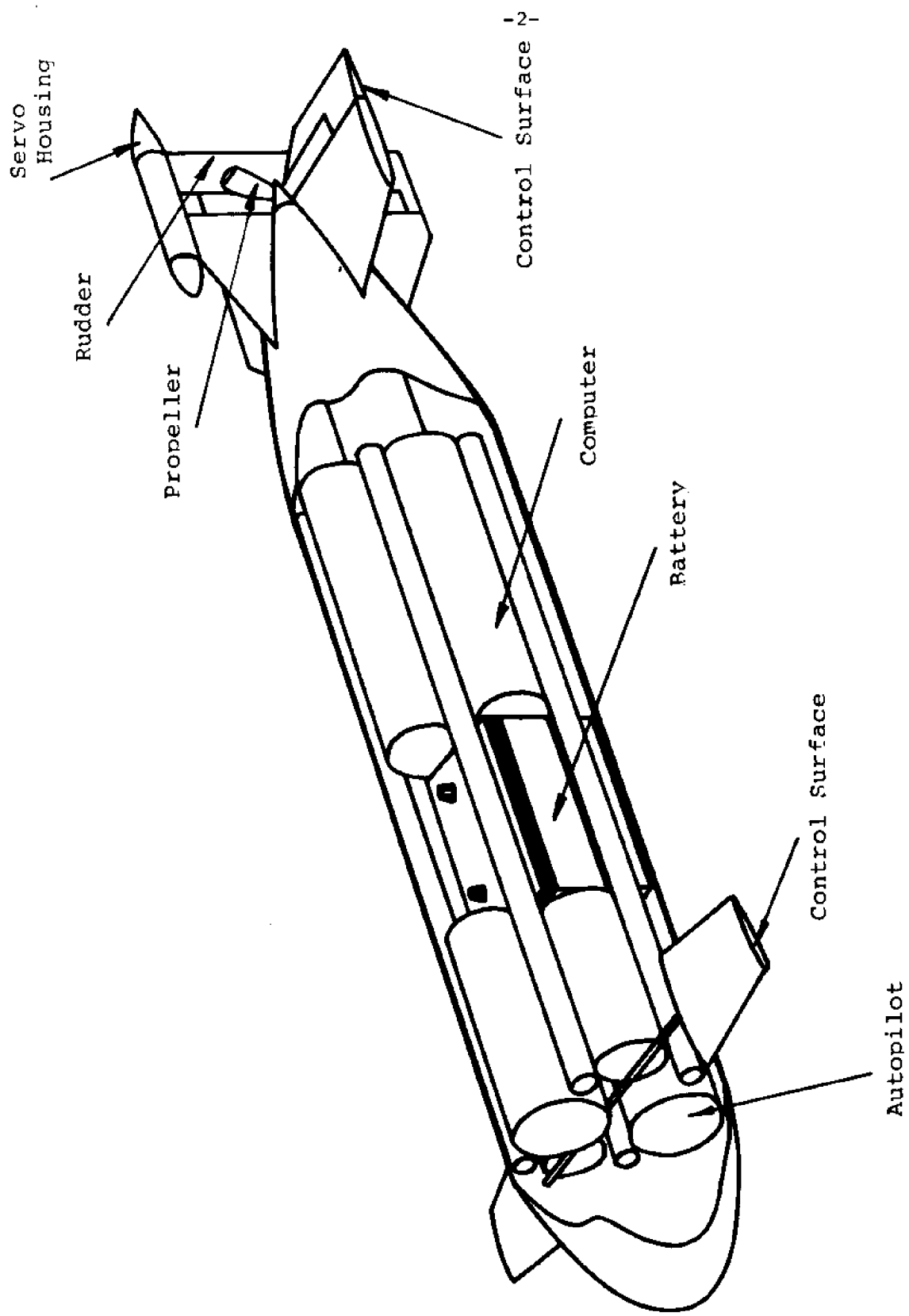


FIGURE 1.1 Preliminary Design Sketch of the Robot Submarine



ship, but this is only half the problem since the operator must know the condition of the vehicle. In addition to having the known vehicle parameters such as attitude and speed, the outputs from bottom finding and collision avoidance sonar would have to be telemetered. This would involve both an excessive bandwidth and unacceptable time lag in the control loop. It was therefore decided to use a two level automatic control system with an analog autopilot maintaining vehicle stability and a general purpose digital computer to handle navigation and routine vehicle status checks and to send commands to the autopilot for course modifications. At the beginning of a mission the computer would be loaded with a detailed set of instructions to enable the vehicle to follow the intended path or search pattern. The system would then be started and the submarine released. At the end of the mission, the submarine would stop and wait to be recovered. This recovery would occur somewhere on the surface in open water, aground at a specified spot or, if a suitable sonar beacon were used, the submarine could actually return to port.

## 2. THE HULL DESIGN

### 2.1 THE HULL STRUCTURE

#### 2.1.1 Preliminary Consideration

The basic shape of the robot submarine was selected as a compromise between good hydrodynamic shape and ease of construction. The cylindrical shape of the center hull portion was used for ease in construction and the nose and tail fairings were added to provide streamlining. A hydrodynamic analysis using an existing computer program was utilized to determine the minimum length of tail fairing that would be acceptable. The selected tail fairing design was considered to provide a reasonable shape with only a small region of expected separated boundary layer.

To further simplify construction, it was decided that the nose and tail should be fiberglass and the center section should be rolled aluminum sheet (.040 in thick), Figure 2.1. The fiberglassing was completed using wooden patterns followed by plastic molds and finally fiberglass. The aluminum sheet had to be sent outside M.I.T. to be rolled because it was too large for M.I.T. facilities.

The pressure housings for the submarine, located inside the free-flooded aluminum and fiberglass skin, were machined PVC plastic pipe with O-ring sealed endcaps. They were to be symmetrically arranged with two six inch diameter tubes one above the other, two four inch diameter tubes on either side and four two inch diameter tubes around the outside, Figure 2.2.

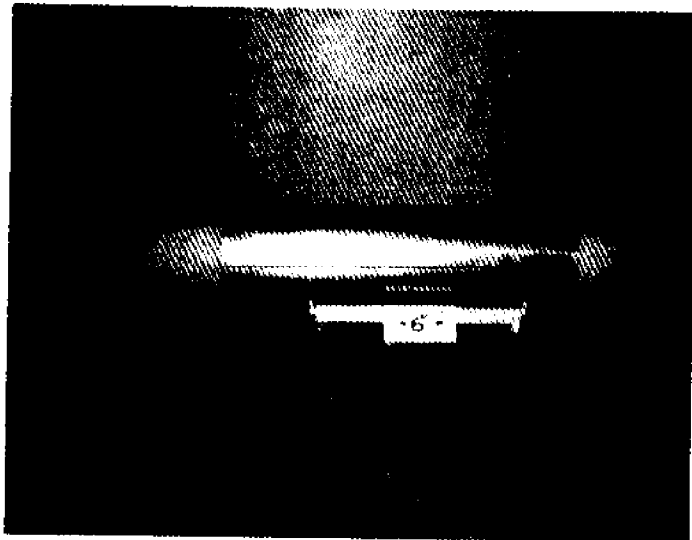


FIGURE 2.1 The Submarine with its Complete Outer Skin.  
The Propeller and Control Surfaces are not  
Attached.

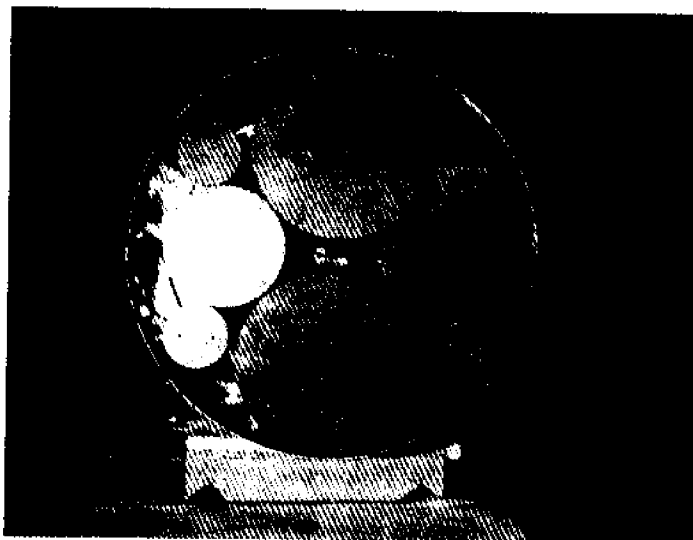


FIGURE 2.2 An Endview of the Submarine with the Nosecone and  
Bulkhead Removed to Show the Cluster of  
2", 4", and 6" Tubes.

Using these preliminary designs, trim calculations were begun to determine the best positioning of payload for stability. In a submarine the optimum trim is to have the center of buoyancy on the same vertical axis as the center of gravity and as far above it as possible. This provides for maximum pitch and roll stability. By calculating the volumes and weights of each component of the sub in terms of one variable, the position of the battery, an attempt was made to adjust that position to achieve even trim. Many values were approximated during the preliminary design, such as electronic payload and motor size, but a position was arrived at which allowed internal construction to begin.

#### 2.1.2 Structural Arrangement

For stiffening and strength, the two inch tubes were made to the full length of the center cylindrical section of the submarine robot. The other tubes were interrupted by the battery compartment. The forward four inch tubes were also shortened to accommodate the drive shaft of the bow diving planes.

The basic design of the PVC pressure housings is a length of pipe sealed with two PVC endcaps equipped with O-rings. The O-ring sits in a groove in the endcap along the inside of the pipe. All surfaces were carefully machined for smoothness and a very tight fit. This design was thoroughly tested using a direct pressure test and further checked by the use of a vacuum test. The vacuum test consists of fitting the endcaps with a tiny hole drilled through and a tapped hole going in only part way over it to fit the screw end of a hand vacuum pump. Evacuating some of the air from a tube seats the O-ring. The hope is that a tube

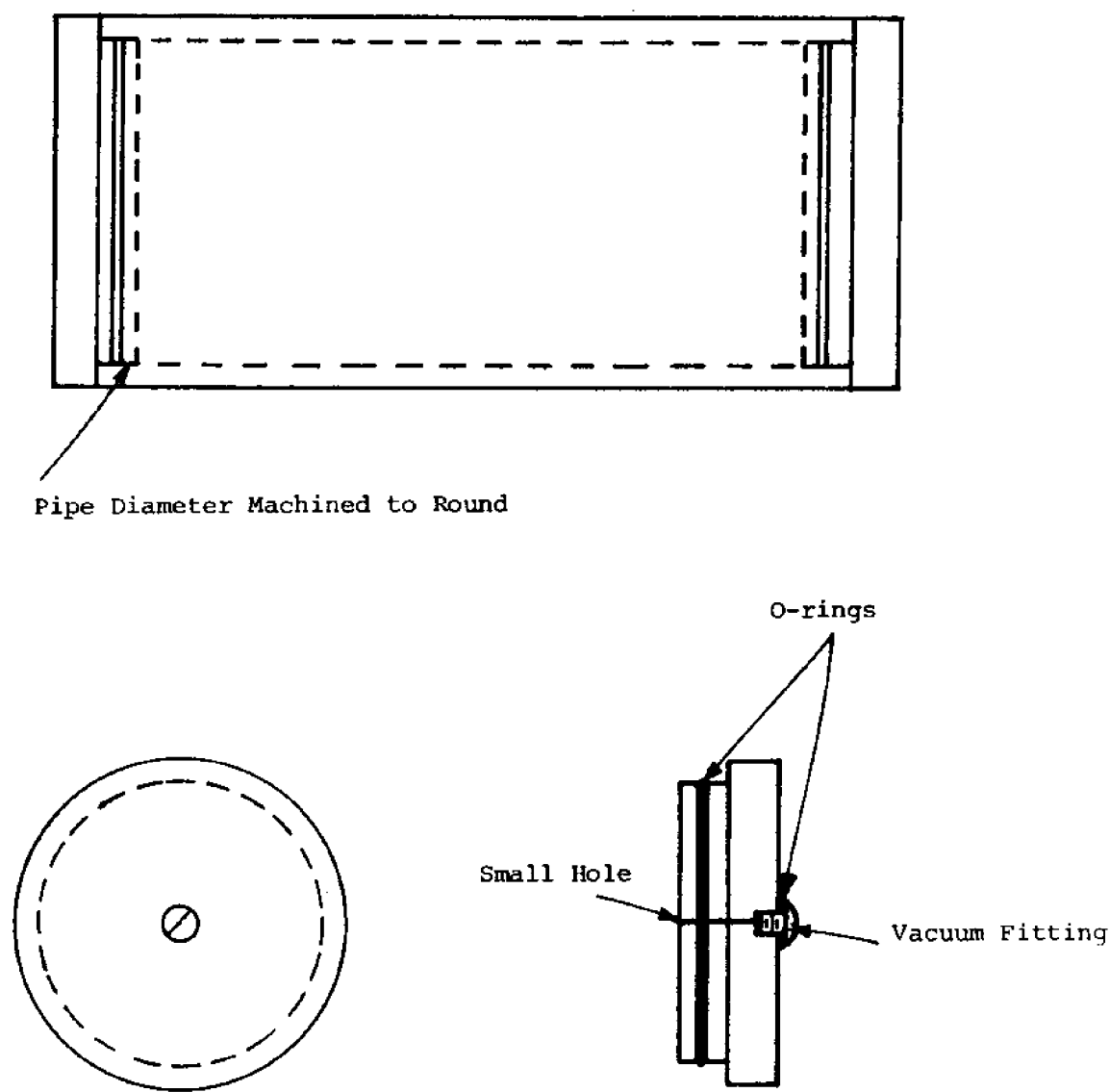


FIGURE 2.3 The PVC Tube Design

that will hold vacuum will not allow water to leak in. Each tube in the sub has a vacuum fitting in its most accessible endcaps sealed during use with a screw with an O-ring under its head. A slight vacuum is applied to each tube before launch to seat the O-rings, Figure 2.3.

The direct pressure tests proved very successful and convinced the group that the housing would easily sustain the planned operating pressure. Failure of samples of the 6 in., 4 in. and 2 in. pipes occurred at pressures corresponding to almost 600 feet; operating depth was planned for not more than 200 ft. The tubes were subjected to 100 psi for one hour without leakages. They also held vacuums of 30 centimeters for prolonged periods.

Aluminum bulkheads were used for aligning and positioning the tubes. The four main bulkheads were located at each end of the center section and fore and aft of the battery compartment. They were made of the same sheet as the outside hull, and when in place with two inch tubes, formed a firm frame for the submarine interior. The two inch tubes were screwed to the first and fourth bulkheads with two screws in each endcap. These endcaps for the two inch tubes had to be cemented instead of sealed with O-rings because of size limitations in machining facilities. The middle bulkheads were positioned by being screwed into PVC blocks glued to the outside of the two inch tubes. These blocks also functioned as sites for the attachment of the hull to the frame, Figure 2.4.

The foreshortened four inch tubes in the bow of the sub presented an alignment problem. This was solved using tie rods running from the

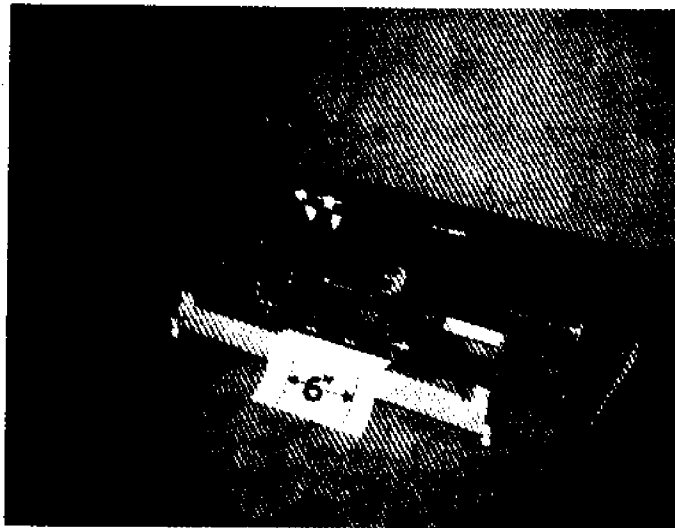


FIGURE 2.4 The Basic Frame of the Submarine Showing the 2" PVC Tubes and Aluminum Bulkheads. The Battery Support Has Been Installed in the Center Compartment

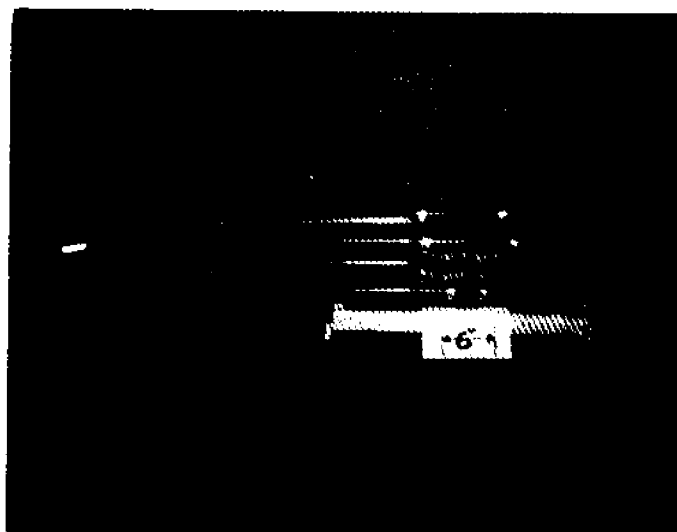


FIGURE 2.5 The Entire Internal Structure of the Submarine Showing the 4" and 6" Tubes in Place, The Battery in its Support and the Tailframe with Motor Tube in Place.

forward endcaps through the second bulkhead and anchored there with nuts. These helped to keep the tubes and their endcaps in place. All the other tubes were restrained by the bulkheads on each end.

The motor tube and tail assembly also presented a difficult problem. Access to the computer, located in the lower stern six inch tube, could only be from the rear. This demanded an easily removeable tail section. The motor tube was mounted in an aluminum bracing system which consisted of four aluminum bars bent to the shape of the tail cone and fastened to the stern endcap of the tube, a PVC endplate and a fifth bulkhead directly behind the fourth, Figure 2.5. The motor tube was also screwed directly to this fifth bulkhead. Support was provided by two tie rods extending through the fourth and third bulkheads and fixed with nuts on the inside of the battery compartment. Because of the shape of the reinforced slots in the fifth bulkhead, removal of the tail section could be achieved by loosening the nuts inside the battery compartment and then lifting up and out on the tail structure. The heavy weight of the tail necessitated reinforcement of the bulkhead with extra aluminum.

The fiberglass tail cone slides over this structure and screws to the aluminum hull. Wiring for the rear servos, located outside the tail, comes through holes in the fiberglass and runs along the leading edges of the stern fins. The endplate of the internal tail structure was cut in PVC to fit the opening in the fiberglass and contains two plastic bearings in the center for the propeller drive shaft.



### 2.1.3 Control Surfaces

After preliminary calculations and design work the control surface designs were arrived at. Each set of planes was to have a fixed and moveable portion. The moveable portions were to be proportioned to shape NACA 0015. The maximum dimensions of the shape were to be a thickness of 0.625 in. and a chord length of 2.75 in. Unfortunately, this shape and dimensions lost accuracy due to hand fabrication and sealing methods. The final shapes were only a good approximation to the design. The fixed portions were rather arbitrarily decided upon and built to the same basic airfoil shape as the planes. All wooden surfaces were sealed with fiberglass resin for waterproofing and strength.

The bow planes were 7.5 in. long and tapered from 4.375 in. at the sub to 3.375 in. in width at the end. These dimensions include both fixed and moveable portions. The fixed section was designed to curl around the moveable plane for protection and support. This hooked tip later proved to be the weakness of the original structure because the wood used was not strong enough and broke off when it accidentally fell from a height of about three feet. This made it necessary to rebuild the fixed portions, using alternative materials of marine plywood and PVC. The PVC versions were thought to be stronger and were used in all the running tests without mishaps.

The bow planes were attached to the outside of the hull just behind the nose cone by means of an aluminum plate screwed to the hull and bolted to the fixed portion of the plane. This plate had a flanged bearing in it for the drive shaft of the plane. The hooked end of the horn also

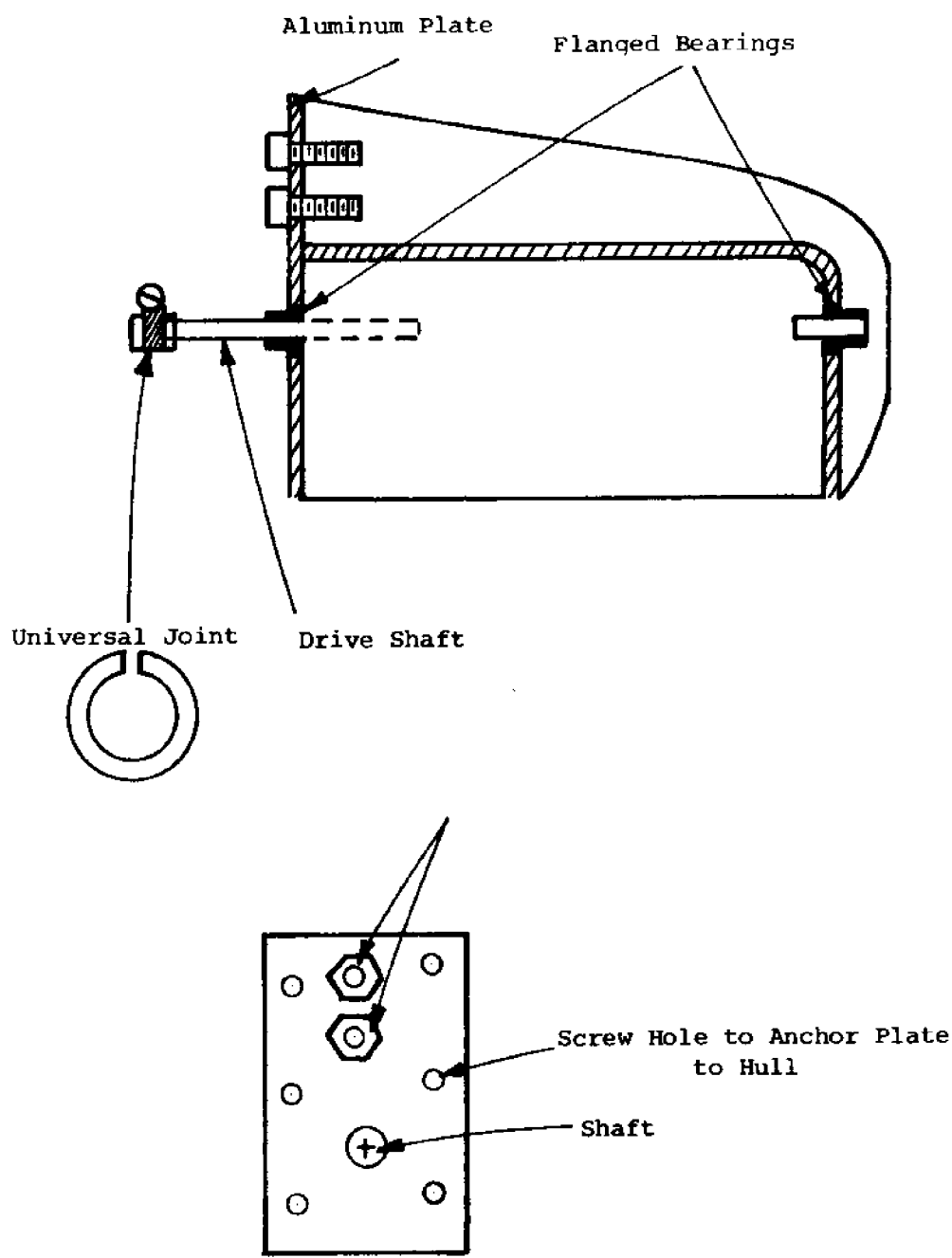


FIGURE 2.6 The Design of the Forward Diving Planes

contained a similar bearing. Small pieces of shafting were fixed in each end of the moveable plane, the outer one mostly for support and alignment. The inside end extended a few inches into the sub and the two sides were connected using another shaft and two simple universal joints. Tygon tubing proved to be too flexible, so PVC was used instead. The universal joint was a thin sleeve with a slot cut through it which allowed a tiny hose clamp to squeeze it tightly around the two shaft ends. The universals allow for slight shaft misalignments but keep the planes moving simultaneously from one motor, Figure 2.6.

The stern fins (fixed) were mounted on the fiberglass tail forward of the propeller. They were hand carved out of pine to provide dimensions and fiberglass to the tail section. They were originally carved to the same airfoil shape as the rudders, but later modified for cables and servo attachments. Fiberglassing proved extremely difficult on such a tight curve, so the only really successful piece of cloth was the one attaching to the tail itself. The others contained so many air bubbles that they had to be extensively ground off. Placement of the fins on the tail was difficult because it was impossible to assume that any of the surfaces were square, plumb or flat. Trying to be as accurate as possible they were placed at 90 degrees to each other and lined up along the center lines of the vehicle.

Aluminum protectors were made to enclose the servo cables and to approximate the correct airfoil shape. They were held on with duct tape for running tests. Mounted on the end of each fin was an aluminum bar used to hold the servo motor tube. These were held to the fin with wood

screws and fiberglassed over for further strength. They extended the length of the servo tube and had clearance holes for the servo drive.

The rudders have fixed shafts and are fitted with flanged bearings so that they turn around the shafts instead of being driven by them. The shafts are held into the aluminum support bars by 1/16 in. pins and go through a PVC center block. One shaft (vert.) goes all the way through, and the other is split into two and anchored into the block with the same type of pin. Originally all the rudders had to be split because they could not be drilled the full 13 inches. The rudder was then bridged back together with a dowel because it must turn as one unit. The other two are independent dive planes and had to be split anyway. They were also notched to allow 30 degrees of freedom to each set on each side. In actual assembly it seemed easier to put these pieces in place before attaching the other sections of the tail, including the propeller, although this made it a little trickier to attach the servos. Lining up the pin holes was rather difficult.

#### 2.1.4 Cables and Cable Routing

Electrical wires for connecting the autopilot, computer, battery and control panel to the sensors and servo motors were made up into nine wire cables. These plugged into the underwater connectors mounted in the endcaps of the instrument tubes. Each cable was strung through Tygon tubing for abrasion protection. Pathways for cables were cut in the bulkheads and laid out for the easiest route.

Three cables extended the full length of the submarine and were routed underneath the battery and along the sides of the lower six inch tubes. These were the autopilot to computer connection and two autopilot to servo cables. Two cables ran up along the side of the rear tubes to join the computer to the control panel, located above the battery. One cable also ran from the control panel over the forward tubes to the autopilot. This cable was replaced by the tether cable during actual test runs so that the sub could be operated from the support vehicle. Two cables came between the two rear six inch tubes to connect the motor to the battery and the autopilot. The cable from motor to autopilot came up in the battery compartment then forward along the top of the forward tubes.

The cables into the tail section for the servo motors had to be separated and were wrapped in tape instead of in tubing. The harness was then positioned by being taped to the motor housing and the ends were strung through the fiberglass cone to the motors.

#### 2.1.5 Lifting Arrangements

The submarine was designed to be lifted by two winches on the support vehicle. Lifting rings fashioned from angled 1/4 inch aluminum stock were used. They were screwed into the first and fourth bulkheads using seven flat headed screws. Some skepticism was expressed as to their strength, especially because they were dimpled (countersunk) in sheet aluminum. Apparently this skepticism was unwarranted though, because they held up very well under test.

#### 2.1.6 Flooding and Draining Ports

Because the sub was free flooded, it had to have an easy method for flooding and draining. This was accomplished by drilling six 3/4 in. holes in the lower skin and by making use of the 1/4 in. gap between the two halves of the aluminum hull. It was feared that the weight of the water would distort the aluminum if it did not drain fast enough. During testing, however, the holes at each end under the battery compartment allowed sufficient draining and no detectable distortion occurred.

#### 2.1.7 Hatch Design

Access to the battery and control panel was gained through a hatch cut in the hull directly above the battery. It was large enough to permit removal of the battery and control panel, and hinged out for maximum working room. The aluminum hull was braced with two support bars on either side of the hatch and there were small stops to hold the hatch in position. The control panel was never firmly attached for the tests and could conceivably be mounted in the hatch itself in the future. During running tests the tether cable came out of the hatch and it was held shut with duct tape.

#### 2.1.8 Handling Arrangements

Care of the sub was fairly simple. Special consideration had to be given to the delicate parts such as the bow planes and servo housings. After each launch the sub was thoroughly rinsed with fresh water and all the tubes were checked for leakage. Connectors were cleaned with an aerosol degreaser.

The submarine was transported and stored on a wooden cradle which has two useable sides. One side is cut with the curvature of the skin and lined with rubber pads and the other is notched to hold just the internal structure resting on the two inch tubes. Its construction, although of strong enough material, must still be considered temporary because the nails should be replaced with screws. Another helpful innovation would be to mount permanent carrying handles. The cradle extends the length of the aluminum hull and has support points under each end and under the battery.

#### 2.1.9 Ballasting Tests

After official christening ceremonies when the robot was named "Albertross" the submarine robot was lowered into Castine harbor on Sunday, July 21, 1974, with exuberance and not a little nervous hesitation. Contrary to some expectations it proved to be very positively buoyant and heavier toward the nose. Original trim calculations were for about five pounds of positive buoyancy, but they were based on a heavier motor and more payload. The tail section which appeared to be deceptively heavier than originally planned, proved to be positively buoyant.

Diving weights were hung at the lifting points and the sub reached neutral buoyancy after 11.2 pounds were added at the nose and 27.6 pounds were hung at the stern. The sub had only one ballasting system onboard at the time of the launch and this consisted of cloth bags hung in the nose and tail cones which could hold up to five pounds of lead shot. Problems arose with this system, however, because the bags collapsed and would not fill, and the rear tubing kinked around the motor housing.

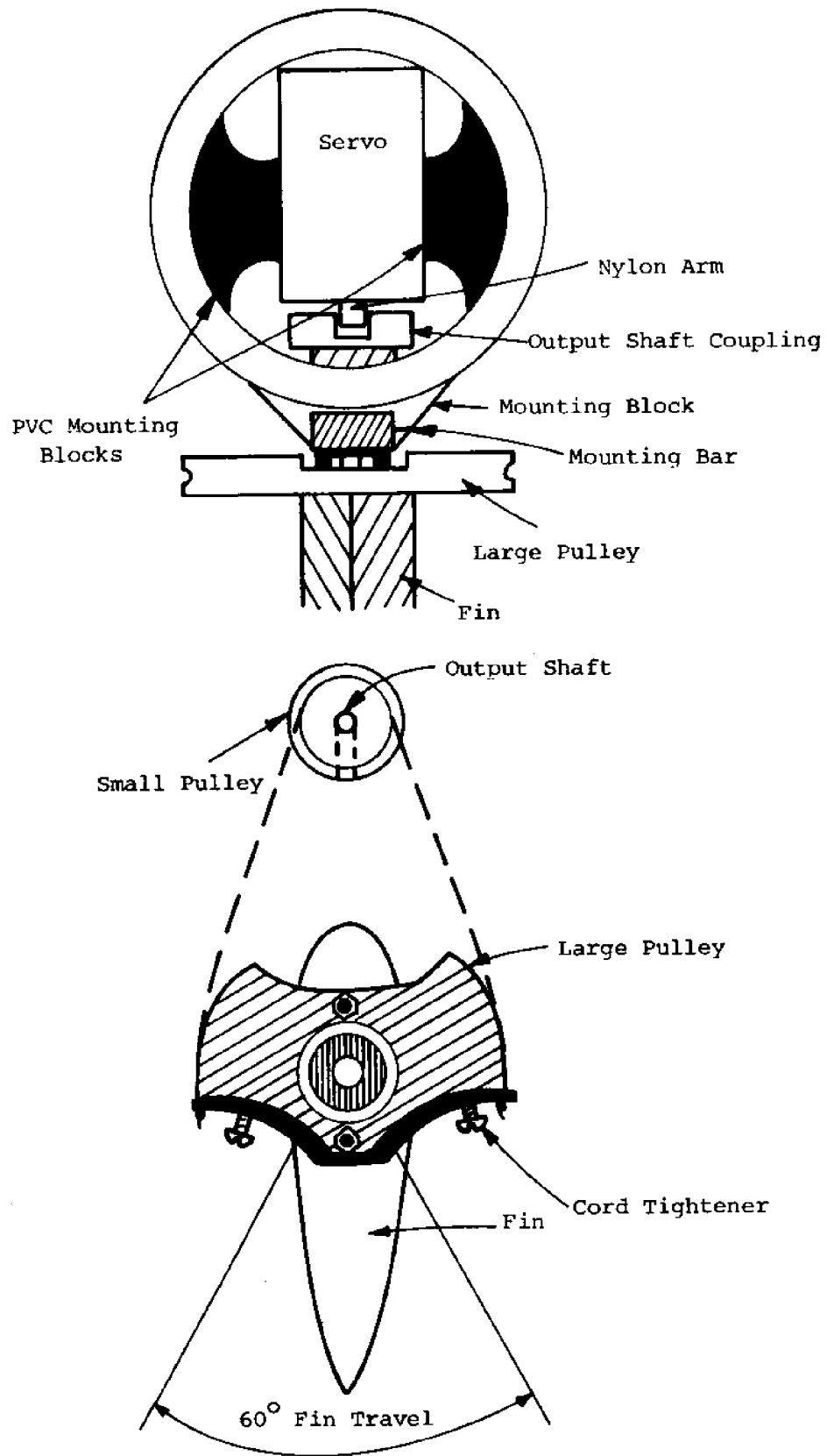


FIGURE 2.7 The Rear Servo Assembly



Two additional ballasting systems were added for subsequent launchings. The bottom two two-inch tubes were filled with water through a hole in one end which could be sealed with a screw and O-ring. This added approximately 11 pounds of ballast. The second method was the construction of a 22 pound lead keel which was bolted to the underside of the sub.

Using these two methods and with the keel located 1/4 inch forward of the tailcone, the sub was neutral and on an even trim. The addition of the water and the keel, both located well below the center of bouyancy, greatly increased the sub's roll stability. Any effect on other aspects of its motion are as yet undetermined.

#### 2.4 THE CONTROL SURFACE SERVO MECHANISMS

The robot submarine has four control surfaces, a rudder, one pair of bow planes, and two independently controlled tail planes. Each of the control surfaces has its own servomechanism to drive it. The servo-mechanism consists of a servomotor (with an integral reduction gear) and a mechanism to couple the servometer to the control surface. The servomotor is activated from the autopilot signals and has an operating range of 220 degrees. Since the control surfaces were limited to a range of 60 degrees there was an effective reduction of nearly 4:1. This was accomplished by two pulleys connected between servos and the control surfaces.

The servomotors were housed in servo-tubes with the output shaft passing through O-ring seals. The original design at the rear servo tubes with the servo tubes supported on fins attached to the fiberglass tail

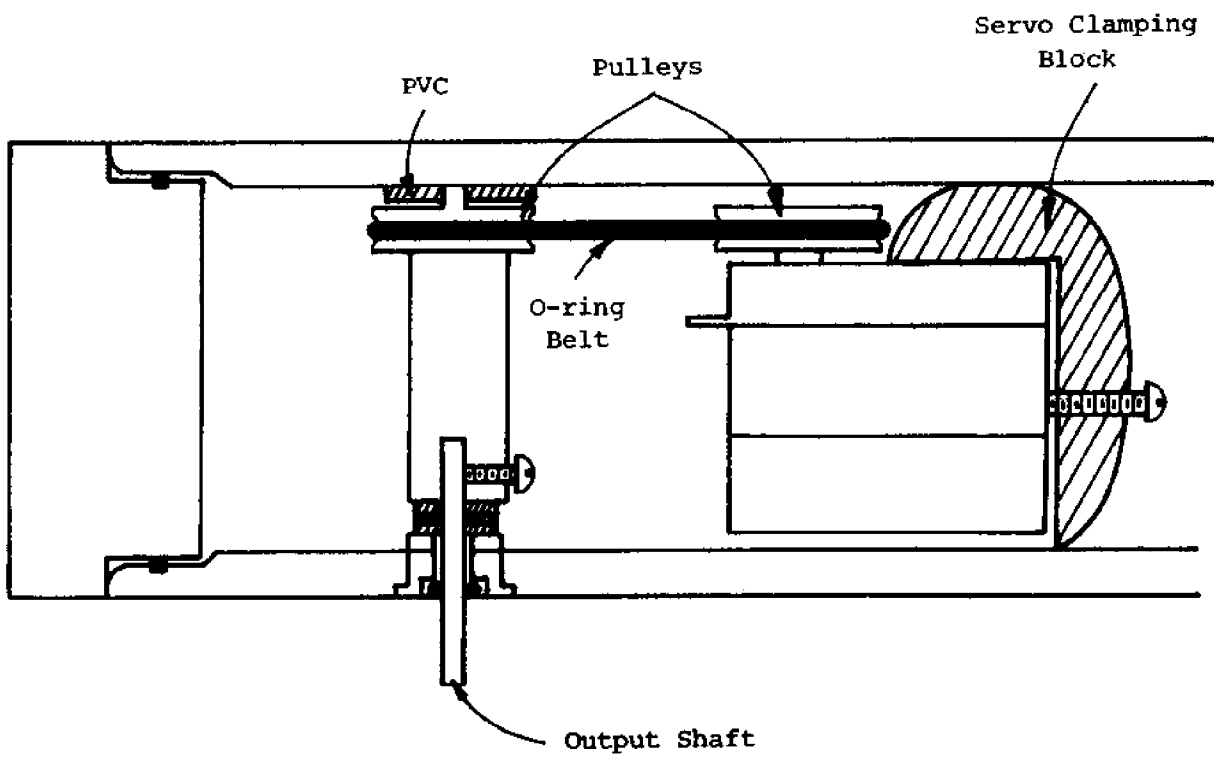


FIGURE 2.8 Modified Rear Servo Design

section is shown in Figure 2.7. When this design was tested it was found that there was the possibility of water leakage through the seal because of the movement of the shaft. It was necessary to redesign the system and provide an extra bearing for the output shaft, as shown in Figure 2.8.

The servo tube for the bow diving planes was mounted inside the nose of the submarine. The freedom of orientation permitted the drive shaft to come through the endcap of the servo tube and this was an easier design problem. The arrangement is shown in Figure 2.9.

The operational reliability and the integrity of the servo-systems were considered to be a major problem in the design of the robot submarine and will have to be improved during the coming year.

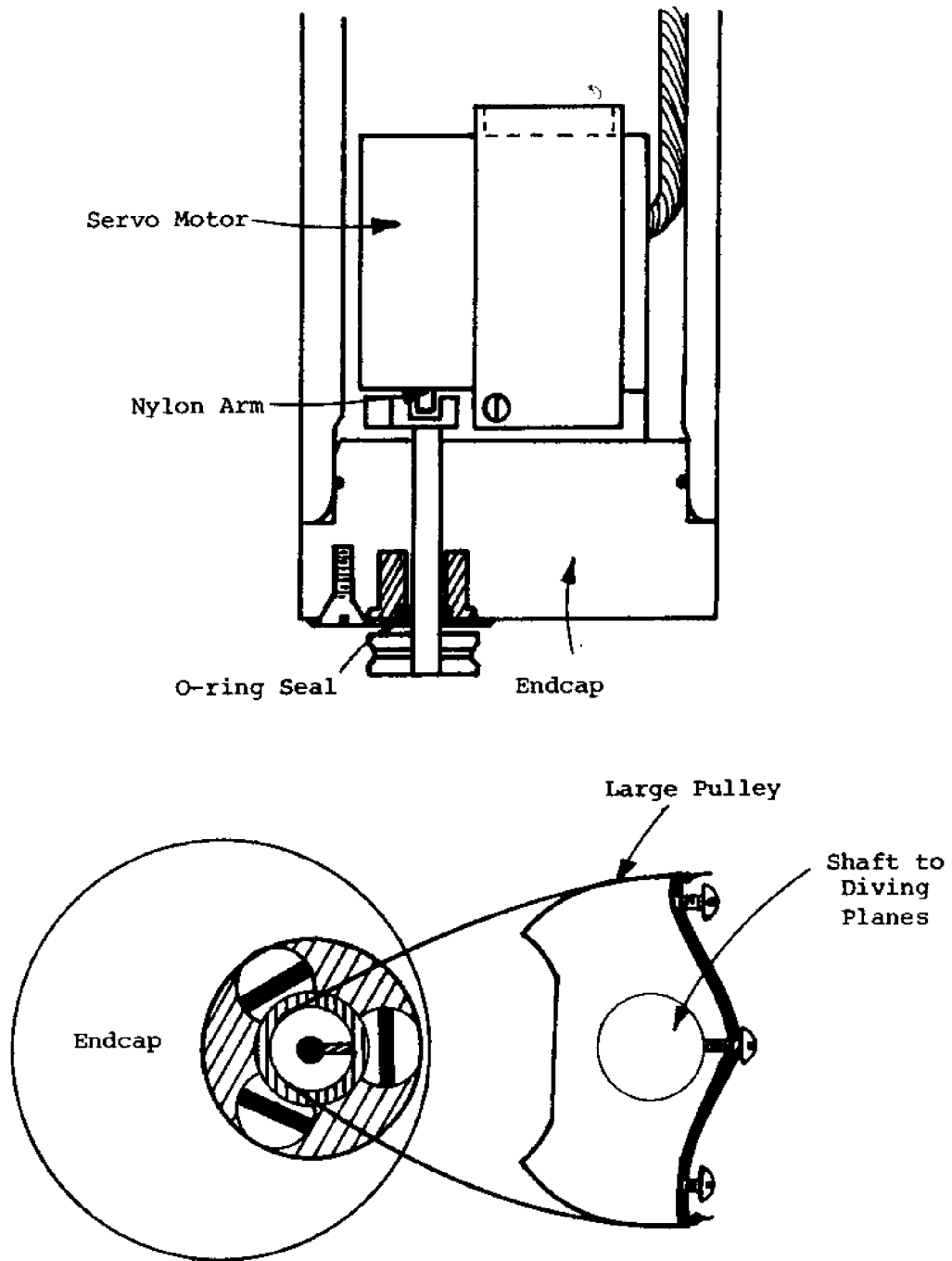


FIGURE 2.9 The Bow Diving Plane Servo System

### 3. PROPULSION AND POWER SUPPLIES

It was assumed from the outset that the robot submarine would use a propeller as the propulsor with the energy supplied from a lead acid battery. Other propulsors, such as waterjets, were not considered because a large propeller would be both more efficient and more convenient to install. Exotic alternatives to the lead acid battery, such as thermal engines, were beyond the scope of the project although other battery systems, both primary and secondary were examined at various times when problems occurred with the pressure compensation system. However, the availability of a lead acid battery of the appropriate size provided the incentive to persevere with that battery.

#### 3.1 THE PROPULSION SYSTEM

##### 3.1.1 Drag Prediction

For preliminary design purposes it was assumed that the drag coefficient was 0.2 based on the maximum cross sectional area of the robot. This drag coefficient gave a predicted drag of about 5 lbf at 5 ft/s (3 knots) for the preliminary design having 14 inch maximum diameter. Later redesign resulted in an increase in diameter to 14.75 inches which increased the predicted drag to about 6 lbf at 5 ft/s.

The calculated effective horsepower (EHP) of the robot was 0.055 which required approximately 0.08 horsepower delivered by the motor and about .14 horsepower delivered by the battery. These values correspond to a propulsive efficiency of about 66% and a motor efficiency of 57%.

It was concluded that a 90 ampere hour battery would provide energy for a 6 hour mission, provided the other components in the robot were designed to be sparing users of electrical energy.

### 3.1.2 Propeller Selection

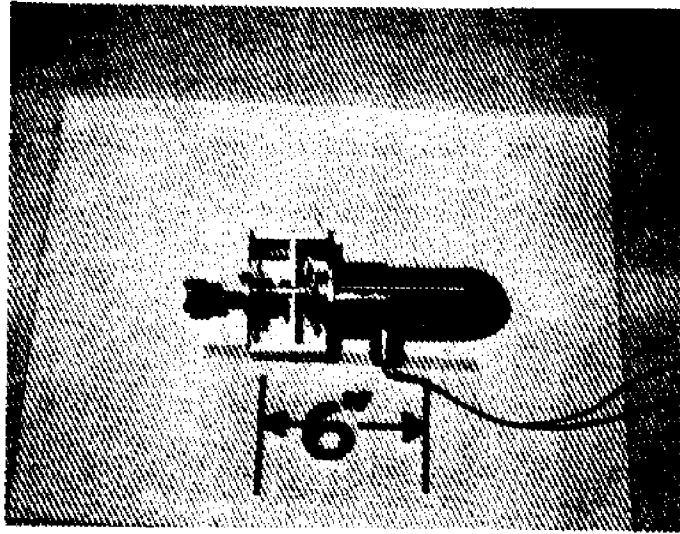
In the initial investigation of propellers the problems of design and manufacture at M.I.T. compared with purchase were examined. It was found, however, that there was a stock of 12 inch diameter aluminum propellers at the M.I.T. propeller tunnel. Measured performance data were available with many of these propellers. The performance of the propellers at the predicted robot design conditions was examined and it was determined that a two bladed propeller would give adequate performance, having a predicted open water efficiency of 73%. This propeller was required to be driven at about 300 rpm.

### 3.1.3 Electric Motor

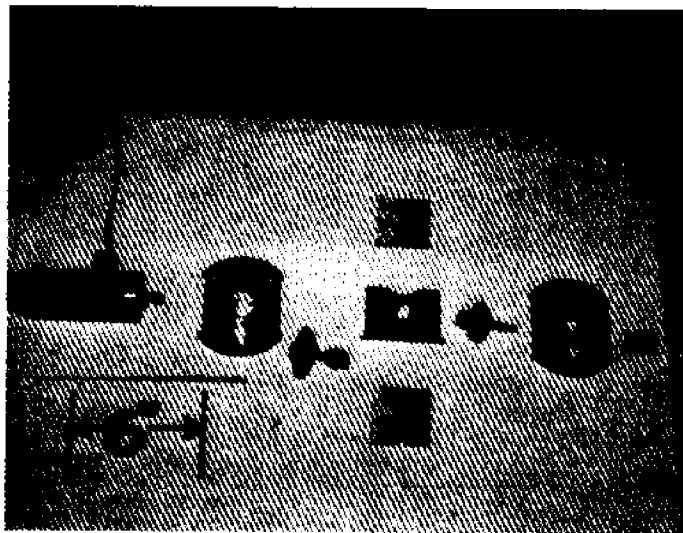
The selected propeller provided the design conditions for the electric motor. A high efficiency dc motor was required that would deliver about 1/10 horsepower at 300 rpm from a 12 volt supply. A thorough search of commercial catalogs showed that there were very few motors rated at 1/10 horsepower operating from 12 volts. There appeared to be two possibilities:

1. rewinding a 12v dc generator from a small car
2. using a trolling motor.

A motor test set up was arranged to test electric motors. A prony brake (rope pulley) was set up to measure torque, the rpm was measured by a magnetic pick up on the pulley and a frequency meter, while the current



a. The Assembled Gearbox Mated with the Trolling Motor



b. The Gearbox and Motor Disassembled to Show Components

FIGURE 3.1 The Motor, Reduction Gear Assembly

and voltage were measured using meters. The tests were conducted using the full battery voltage.

The characteristics of a Saab generator operating as a motor and a trolling motor were obtained using the experimental arrangement. It was found that the Saab generator had a measured efficiency of only 33% when the output was 0.08 H.P. at 1,000 rpm. The trolling motor had an efficiency of 56% with an output of 0.08 H.P. at 3,000 rpm.

The trolling motor was therefore selected as the drive for the two blade propeller. A reduction gear was required to reduce the rpm from 3,000 to 300.

#### 3.1.4 Reduction Gear

The gear box was designed as a double reduction to fit within a 6 inch PVC housing with the output to the propeller at the center of an end cap via O-ring seals. The gear casing was constructed in aluminum and the shafting, gear wheels, and bearings were selected from components available locally. Photographs of the electric motor and reduction gear are presented in Figure 3.1.

#### 3.1.5 Predicted Performance

The predicted performance of the robot with the selected propeller, motor, and reduction gear is presented in the accompanying table.

Robot Predicted Performance

Drag Coefficient	Speed ft/s	Propeller rpm	Current amps	Duration Hours	Range Miles
0.2	4.9	285	8.5	6.4	21.5
0.4	3.9	280	9.0	5.0	13.3



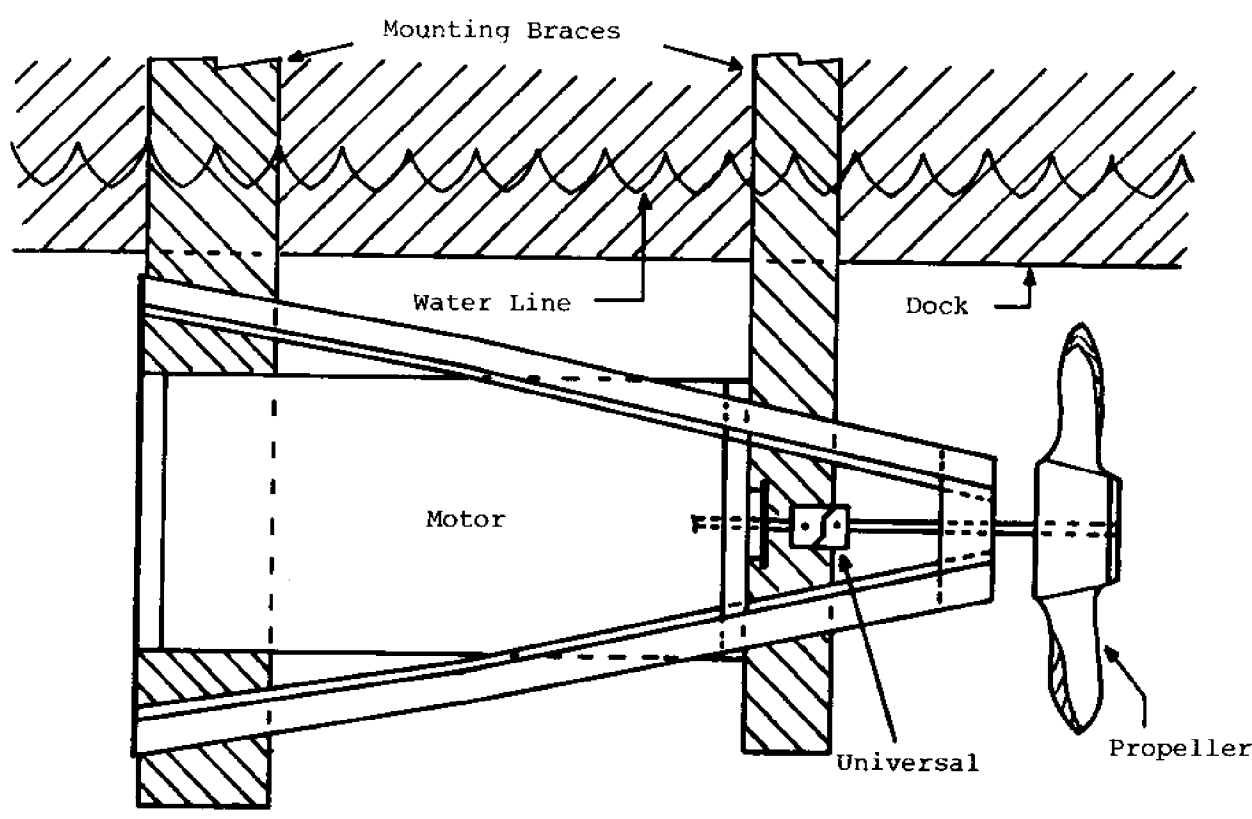


FIGURE 3.2 Mounting for Endurance Tests

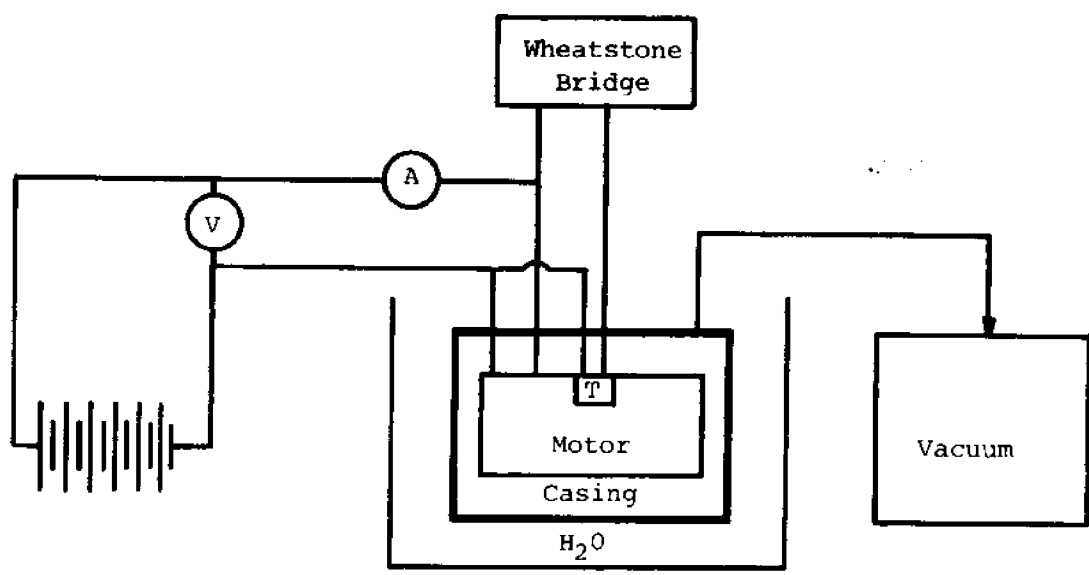


FIGURE 3.3 Block Diagram of Monitoring Devices

In the performance prediction it was assumed that average electronic current was 1 amp and that 96 ampere hour capacity of the battery was reduced because of low operating temperature and because of the relatively high current drain.

#### 3.1.6 Propulsion System Development

During preliminary testing it was found that there was rather high friction in the propeller shaft. There was slight misalignment between the motor housing and propeller bearing. This was corrected by inserting a small universal joint in the propeller shaft. Slight modifications were also made to the reduction gear to improve the location of the bearings.

It was decided to run an endurance test on the propulsion set up to see if the O-ring seals were adequate and also to determine the temperature rise in the motor.

The tests were conducted on the propulsion system alone off the floating dock at Castine, Figure 3.2. During the tests the following measurements were taken:

1. the vacuum in the motor housing
2. the temperature of the motor
3. the battery voltage
4. the current delivered

The test arrangement is shown on Figure 3.3.

The endurance testing showed that the system could operate successfully over a period of 5 1/2 hours. The vacuum was maintained

during the test but the motor temperature rose to 71°C. This temperature is considered to be too high and it is recommended that a method of providing a heat path to the water should be designed.

Inspection of the components after the test period showed that the components were satisfactory although there were signs of wear on the dynamic O-ring seals. The seals should be replaced after about 6 hours of operation.

### 3.2 THE BATTERY SYSTEM

The battery selected for the robot was a 96 ampere hour automotive battery. It weighed 55 lb in air and its outside dimensions were 11.75" x 6.5" x 8". Due to space and weight limitations the battery could not be placed in a special container to withstand the water pressure. Instead a pressure equalizing system was designed. The design had to take account of the following factors:

1. hydrogen venting
2. pressure equalization
3. terminal sealing with easy access for electrical connections.

#### 3.2.1 The Battery Sealing and Pressure Compensation

It was decided to use light mineral oil as the pressure compensation fluid. The mineral oil floated on top of the electrolyte and transmitted the ambient water pressure utilizing a small bladder. The hydrogen gas that is given-off during charging and discharging was allowed to escape by means of a special valve described later. From measurements on a single cell it was concluded that about 50 cubic inches of gas would have to be vented during a six hour mission.

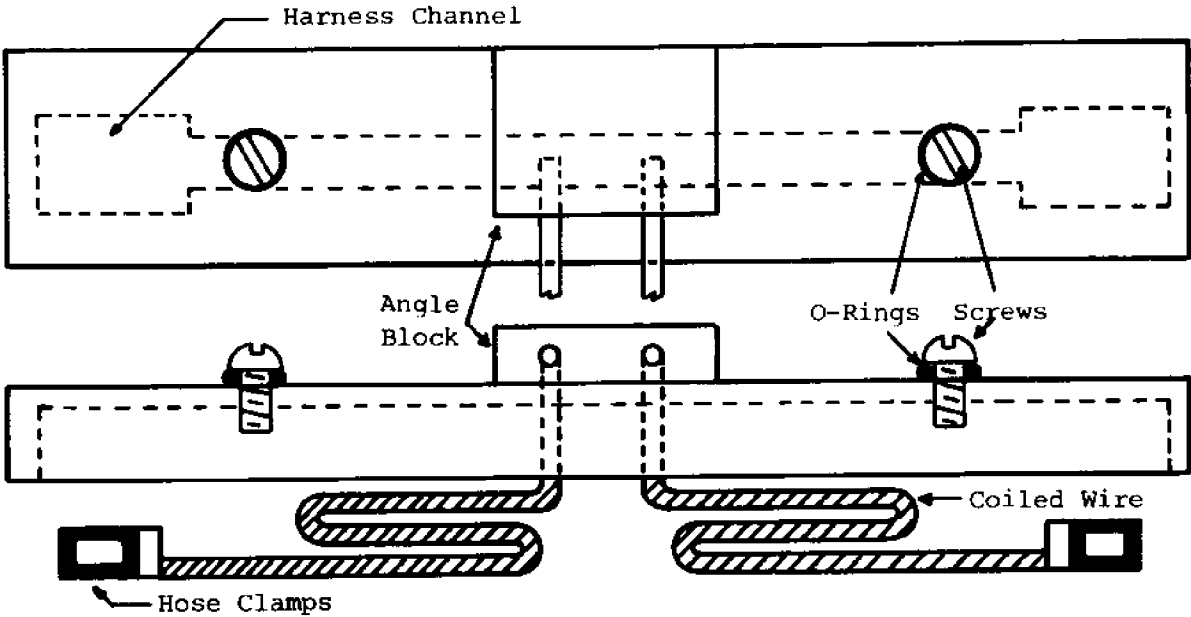


FIGURE 3.4 Terminal Connections to the Battery

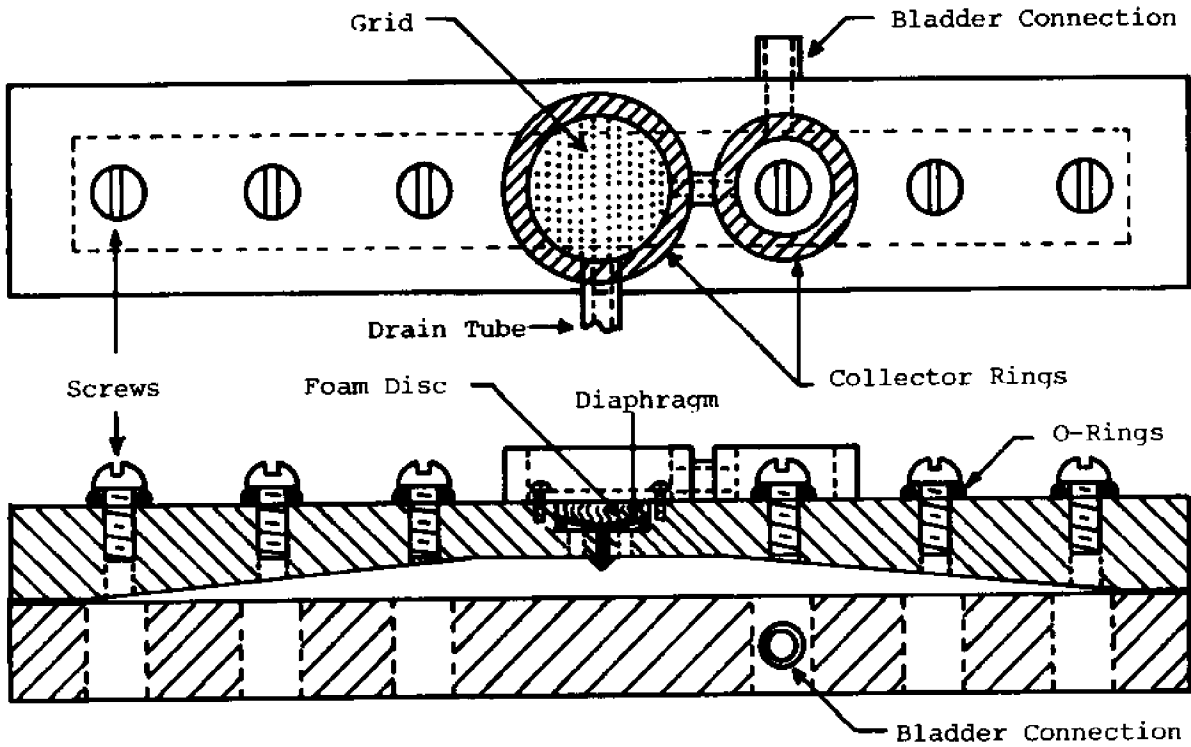


FIGURE 3.5 Collection and Expulsion Blocks for the Battery

One inch thick PVC was the material chosen for the construction of the additions to the battery. One block 11.1" x 2.25" was used to seal the battery terminals. This block and the wire connections are illustrated on Figure 3.4. A second block was placed over the cell holes on the top of the battery to collect the hydrogen. A third block was placed above the second to collect the gas and vent it, as shown in Figure 3.5. The check valve was composed of a neoprene diaphragm from scuba equipment seating on an O-ring.

The PVC blocks were cemented together and then sealed to the battery top using silicone rubber cement. Two large hose clamps were placed around the battery and the PVC blocks as straps, to improve the integrity of the battery system.

Several forms of oil bladders were tried for pressure equalization. The method finally selected utilized a neoprene glove as the bladder. A small hose was used to connect the block on the battery top and the bladder, which was placed in a canvas bag for protection.

One problem was observed with the venting system. It appeared that hydrogen did not rise through the electrolyte quickly enough. Gas was trapped beneath the surface and displaced oil. The system vented oil instead of gas. It was concluded that the valve opened at a very low pressure. A thin foam neoprene disc was made to fit over the valve requiring a greater pressure to vent. This improved the gas venting but was only a temporary measure as the foam would compress at depth. An improved valve system is required.

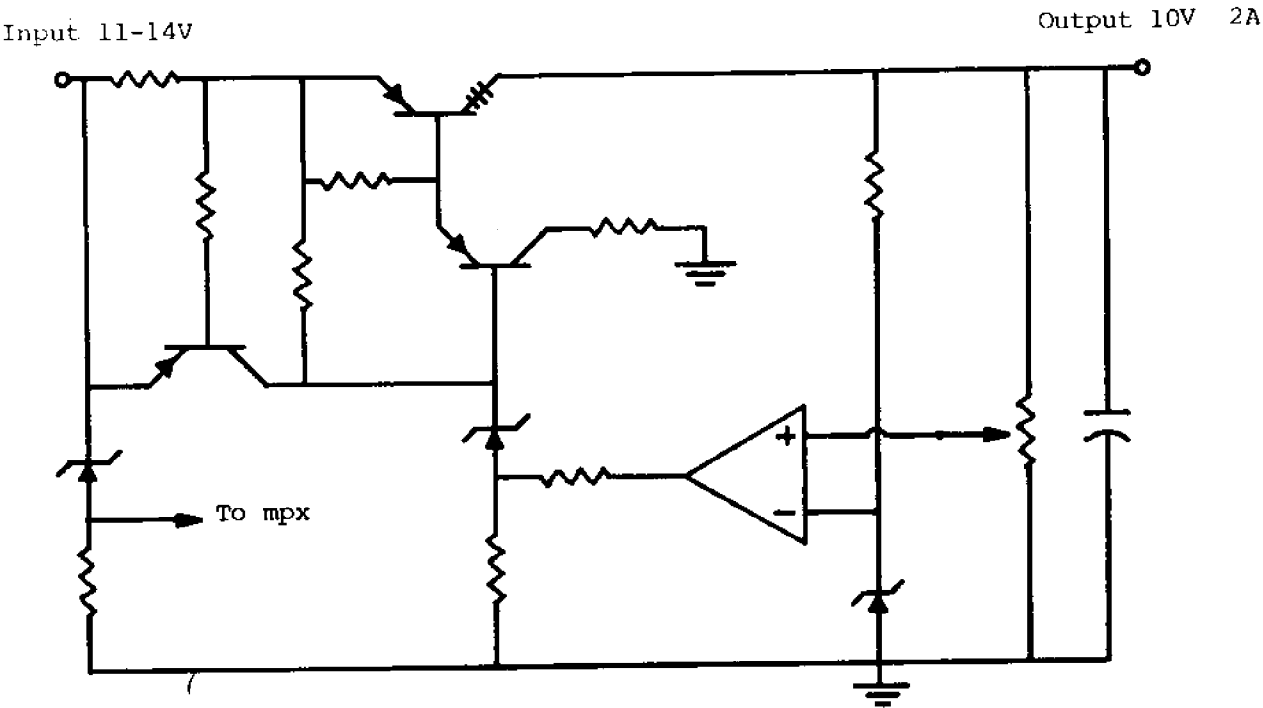


Figure 3.6 The 10 Volt Regulator Circuit

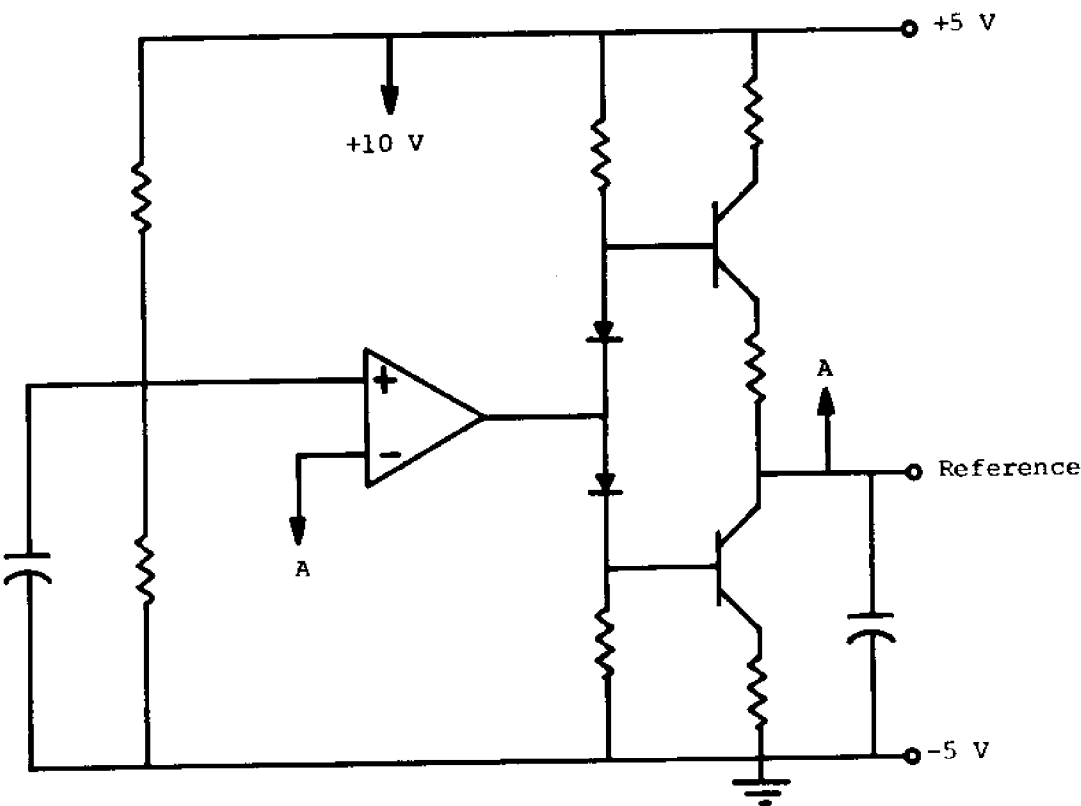


FIGURE 3.7 The + Volt Supply

### 3.3 THE POWER SUPPLIES

The battery is connected directly to the motor tube to drive the propulsion motor. The twelve volt supply is then taken to the autopilot tube where the regulators are situated. Regulated supplies are provided for the electronics and the servomotors.

#### 3.3.1 The Propulsion Motor Supply

The motor tube contains the relays and filters in addition to the propulsion motor, these are the main on-off latching relay and the forward and reverse relays. A filter network was incorporated to reduce the noise spikes on the power line due to the motor.

#### 3.3.2 The Regulated Power Supplies

Three power supplies were developed and built to operate the onboard sub electronics. The computer has two other power supplies built on the computer boards.

The first regulator was designed to convert the main battery supply of from eleven to fourteen volts to a constant ten volts. The supply voltage regulates up to two amps at which point it automatically current limits. Since only a one volt drop could be tolerated across the regulator, the circuit of Figure 3.6 was developed.

The second supply was a standard five volt supply that had to both source and sink current to operate the many operational amplifiers in the submarine, Figure 3.7.

The third supply was rather unique. A five volt switching regulator was developed to operate the servo motors. This supply had to deliver up to two amps. Since the load was not constant a standard

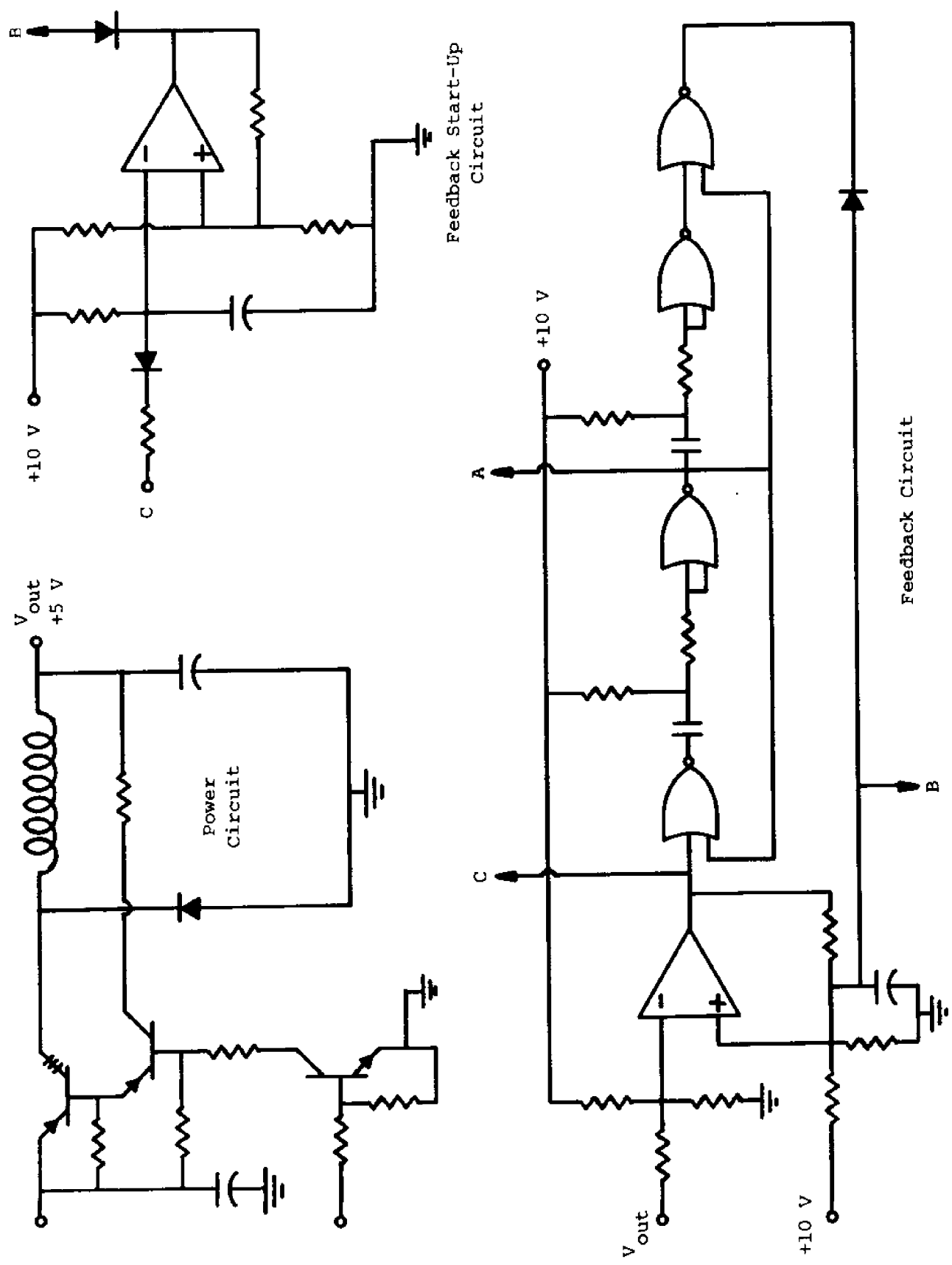


FIGURE 3.8 5 Volt Switching Regulator



switching regulator design could not be used. Because of this varying load, the standard regulator of this type would overshoot considerably and possibly cause damage to the servo motors. A linear regulator used for this application would be too inefficient. With an input voltage of twelve volts and an output of five volts there would be seven volts dropped across the regulator. At two amps this would mean fourteen watts dissipated in the regulator which would not be tolerable. The switching regulator design of Figure 3.8 was used. To prevent over-shoot a switching control circuit with constant off time was developed. This maintains high efficiency and controls the overshoot. The two power transistors, one on the ten volt regulator and the other on the five volt switching regulator were mounted on the chassis of the autopilot package so that they are properly heat sunked.

The ten volt series regulator and the five volt operational amplifier supply function as specified and designed. The design specifications for the five volt switching regulator were for only a five millivolt ripple so that TTL circuitry could use this supply if ever added to the sub. The circuit, however, has a two hundred millivolt ripple which is too large to operate TTL circuitry but would not effect the servo motors. The problem should be easily remedied by replacing the five thousand microfarad capacitor with one which has a lower capacitance and the switching diode with one that has a much faster switching time.

The three regulators were built on one circuit board and is contained in the autopilot package.

A circuit consisting of a resistor and a zener diode was added to the ten volt supply so that this supply could be connected to a channel in the multiplexer link. The circuit is added at the input of the regulator so that it directly monitors the battery voltage. A multiplexer channel was also added to the five volt switching regulator output so that it can also be monitored.

### 3.3.3 The Connectors and Cables

A large number of waterproof cables and connectors were required in the submarine to distribute power and signals to all of the various housings. The final system has ten separate cable harnesses, with nineteen bulkhead connections and two cable connections.

Several commercial connector systems were considered, but they were all somewhat bulky and very expensive. In order to conserve both space and funds, a connector system was developed using standard nine-pin tube sockets and plugs. All solder connections were encased in epoxy resin, and mated connector pairs were sealed with a piece of soft PVC tubing.

Both the male and female cable connectors were moulded in the shape of short cylinders approximately one and one quarter inches long and three quarters of an inch in diameter. The first one half inch of the cylinder (opposite the cable end) is formed by the phenolic body of the connector, and the back portion is epoxy resin. The resin seals the wire to the connector, provides strain relief, and helps to form a seating surface for the soft PVC tubing.

Instead of directly connecting the internal wiring of a particular unit to the bulkhead sockets before sealing them, two inches long copper wire pins are used to pass through the bulkhead. These pins are sealed with epoxy resin inside a short piece of three quarter inch outside diameter PVC pipe. The pipe is fastened by the epoxy to the back of the phenolic socket to provide a seating surface for the soft tubing, and to allow a strong cement bond to the PVC housing material.

Once the connectors are made, they are mated and then sealed with a short section of three quarter inch inside diameter soft tubing lubricated with petroleum jelly. This tubing is secured around the connector body with stainless steel screw type house clamps, or with several turns of galvanized wire if space is critical.

The actual wire used for the cables was 600 volt PVC insulated hook-up wire. The wire was color coded to ease connector wiring and trouble shooting. PVC insulation was selected to provide good bonding with the epoxy. Fourteen gauge wire was used for main power lines, and twenty gauge wire was used for signals and small power connections.

Soft PVC tubing with occasional drainage holes cut in it was used to protect most of the cables from abrasion. The rear servo harness has several branches which have to pass through tight places, where the soft tubing would be too bulky. Therefore, a heavy layer of plastic electrical tape was used instead. The connections at the branch points were sealed with a special putty tape designed for underwater use.

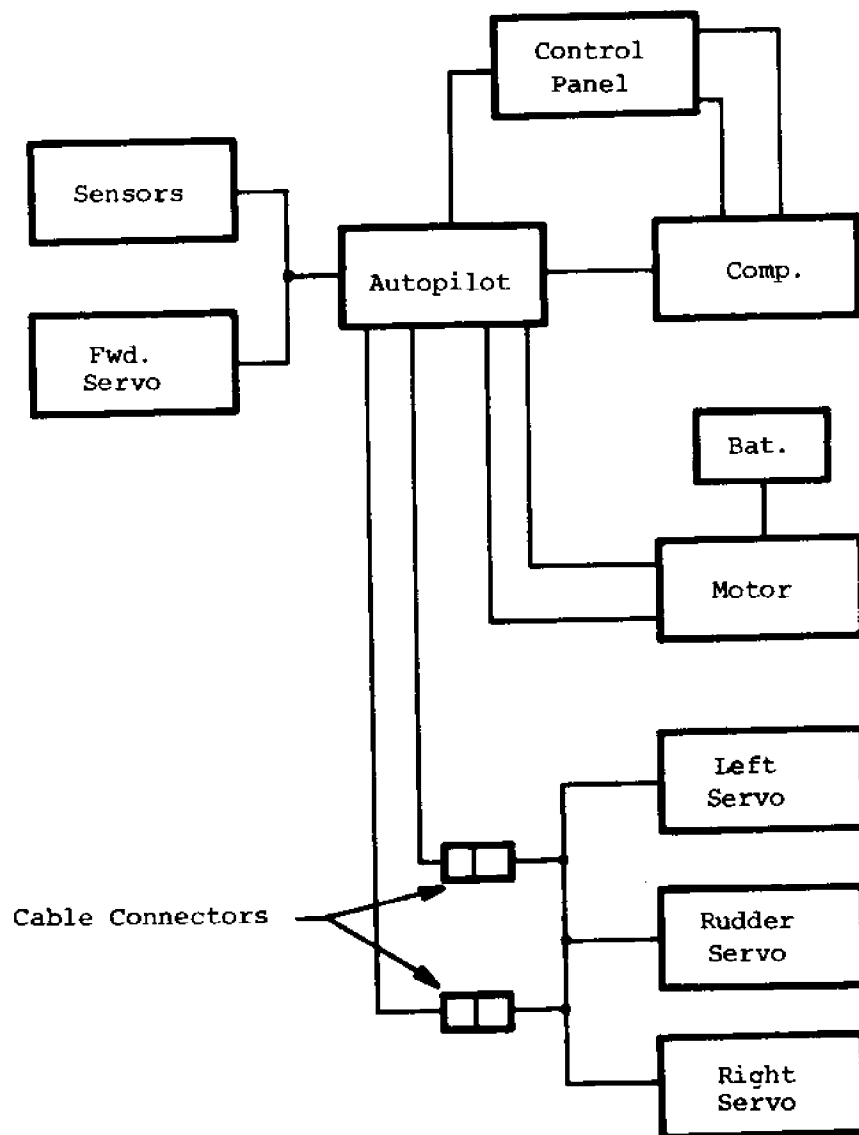


FIGURE 3.9 Cabling Diagram

This connector system has been tested at 100 p.s.i. for four hours without any sign of leakage, and there have been no problems directly traceable to a connector failure on the submarine thus far. Figure 3.9 shows a block diagram of the cable connections for the entire submarine.

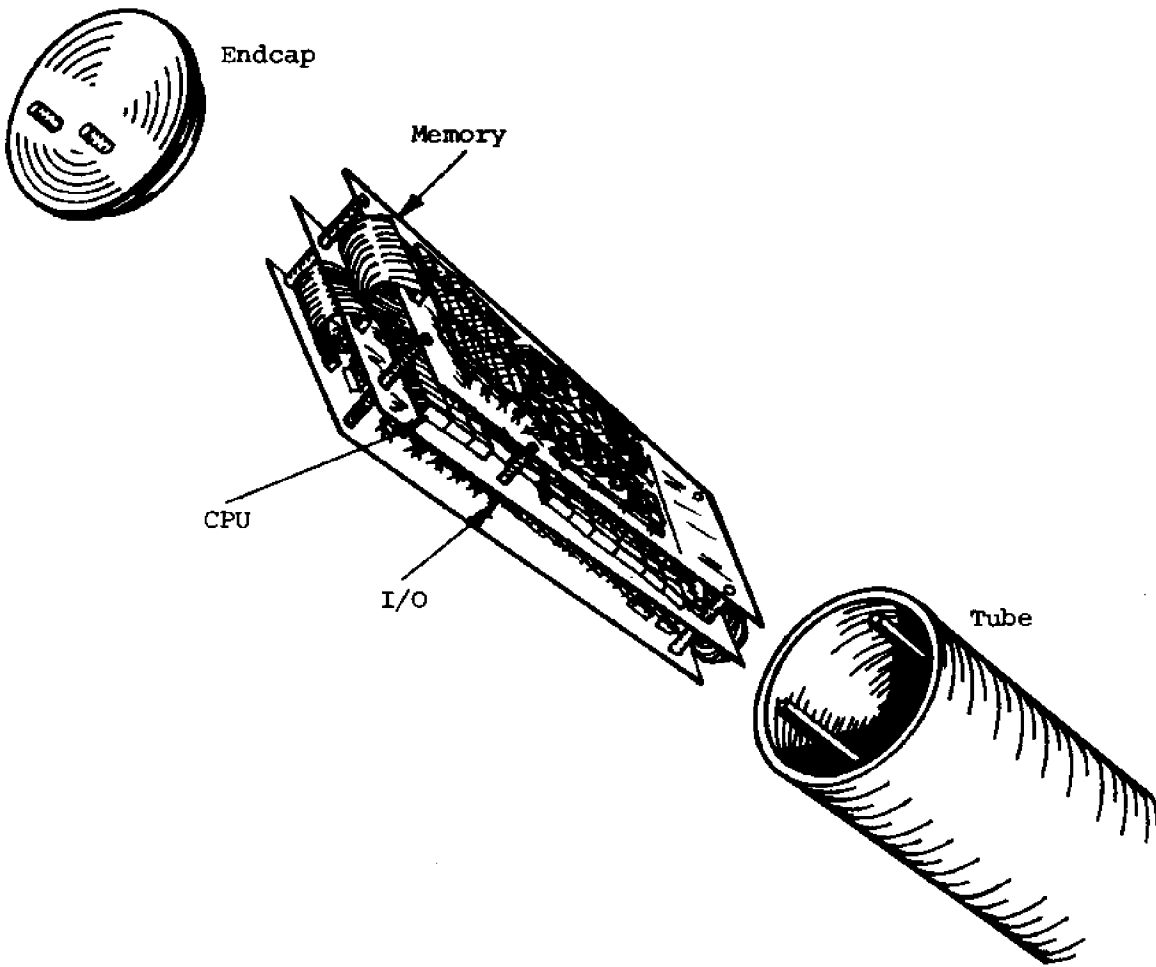
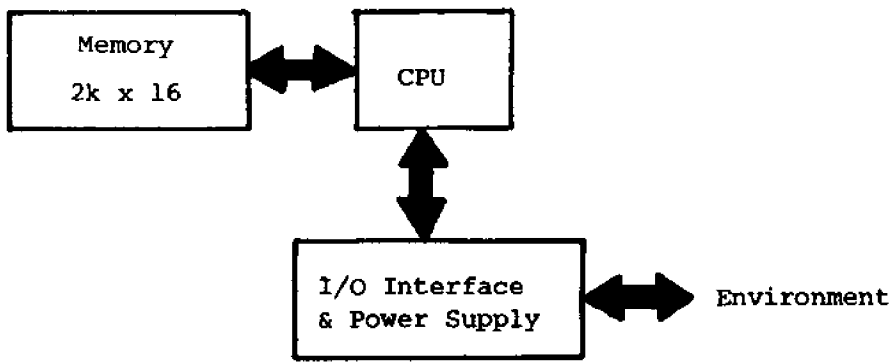


FIGURE 4.1 Computer Architecture and Construction

#### 4. THE ROBOT COMPUTER SYSTEM

A small digital computer has been designed and built for the robot submarine. The purposes are to set the requirements for the autopilot, take control of the robot in emergencies, and to collect and reduce data from the sensors and scientific instruments.

The architecture of the computer is, perhaps, similar to the 12 bit PDP 8 series (Digital Equipment Corp.). However, its 16 bit wide data paths and rich instruction set give it capabilities similar to the Nova Series (Data General Corp.). Due to the requirement of low power consumption in the robot, the computer is almost an order of magnitude slower than the Nova (typical instruction times are 12 microseconds compared with 1.5 microseconds).

Modern digital computers generally have three parts:

1. a central processing unit which executes the instructions and operates on stored data
2. a memory unit, which stores data and instructions for processing
3. an input/output interface which exchanges information between the computer and its environment.

The computer designed for the underwater robot has this architecture, as shown in Figure 4.1. The three units of the computer were constructed on separate computer boards to be placed in the stern lower 6 inch tube, Figure 4.1.

Descriptions of the three units are presented in the following sections together with details of the software. In addition, peripheral

components associated with the input/output function are described. This peripheral equipment includes the robot control panel, the portable tape reader, and the interface unit for the teletype and papertape reader.

#### 4.1 THE CENTRAL PROCESSING UNIT (CPU)

The CPU was designed using lower speed CMOS<sup>1</sup> rather than higher speed TTL<sup>2</sup> components. The decision was based on the requirement to minimize power consumption, mentioned earlier, although it resulted in slower operation. Nevertheless the computer can process over 10,000 instructions in the time that the robot takes to move 1 foot through the water at full speed.

The CPU has two main subsystems, the control logic system and the data paths. The control logic was constructed from about 50 integrated circuit (IC) gates and decoders. The data paths are composed of about 80 IC multiplexers, adders, registers, transmission gates, and arithmetic logic units (ALUs) as shown on Figure 4.2.

In normal operation the program counter (PC) holds the memory address of the next instruction in the program, so at the beginning of the instruction it is given to the memory. The memory responds by feeding the word stored at that location into the decoder which splits it into an operator and the memory address of the operand. Now, there is a pause while the operand is taken from memory. At this point the arithmetic logic unit (ALU) takes over and performs the specified operation (e.g. addition) with the operand from memory. The result of the operation is kept in an internal memory of the CPU known as the accumulator. The cycle is then

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<sup>1</sup> CMOS - Complementary Metal Oxide Semiconductor

<sup>2</sup> TTL - Transistor Transistor Logic



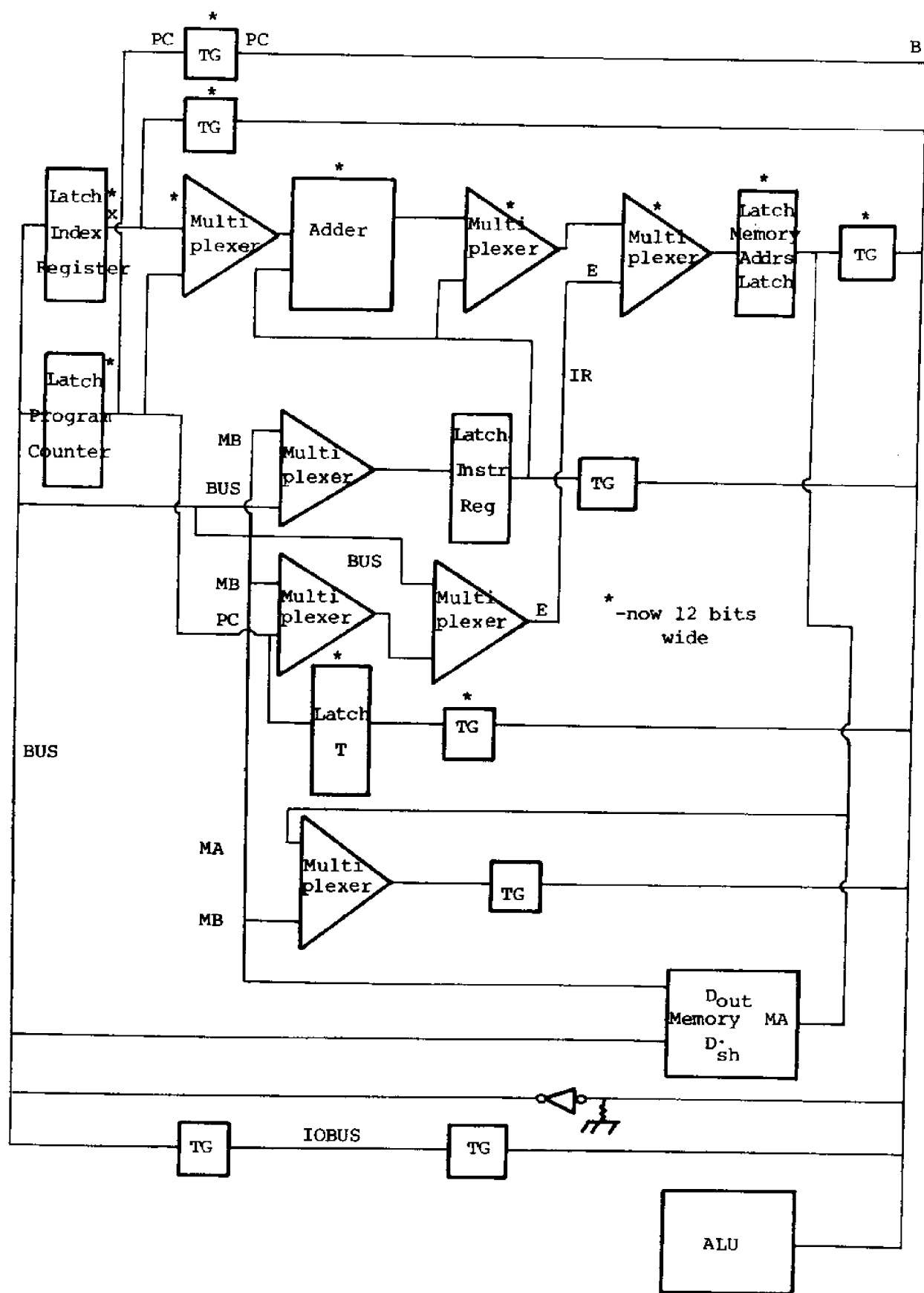


FIGURE 4.2 Data Paths for CPU

repeated on the next instruction. These operations are described with reference to the times at which they occur in the following paragraph.

A representative cycle of the CPU is executed in 8 memory cycles during which the control logic provides the following data path operations for the 8 periods:

1. The instruction is placed into the instruction register and decoded. The address of the first memory reference is generated using the program counter (PC) register, the index register, and the last 9 bits of the instruction.
2. If this is an indirect instruction then the memory is read and the contents placed in the memory address latches for the next read instruction.
3. The operand is read from memory.
4. The operand is gated onto the ALU bus, the operand code is then applied to the ALU and the ALU clock is applied.
5. This is the ALU settling time.
6. Memory write operations are performed if necessary.
7. The program counter (PC) is loaded onto memory address register.
8. The next instruction is read.

The CPU was designed in conjunction with the software which is described later.

#### 4.2 THE COMPUTER MEMORY

##### 4.2.1 Technical Description

The memory unit stores 2048 words of 16 bits each. Its design is centered about sixteen semiconductor memory chips, which use pMOS circuitry to store 2048 bits each. An 11-bit code identifies the address (location in the array) being requested.

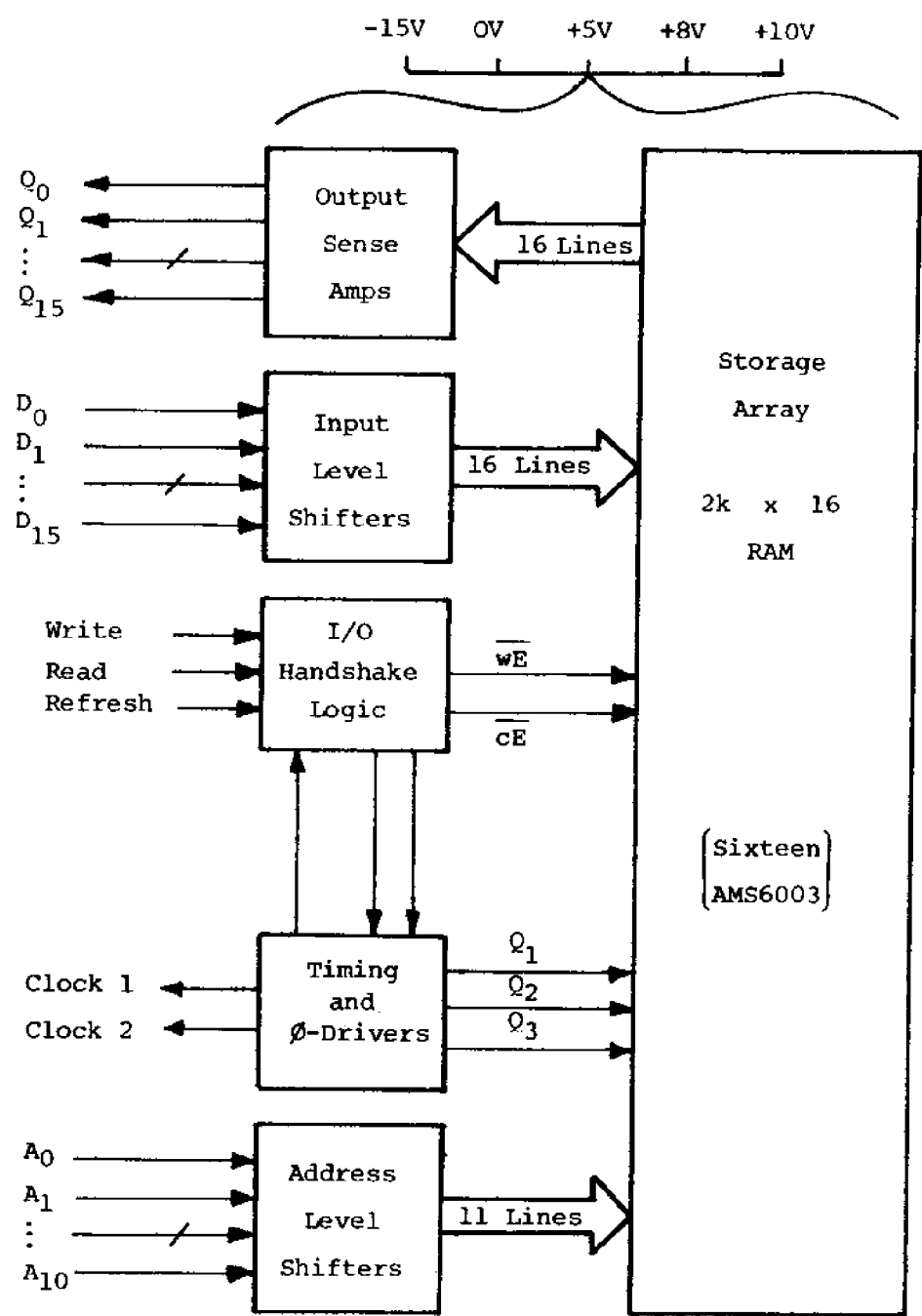


FIGURE 4.3 Memory Architecture

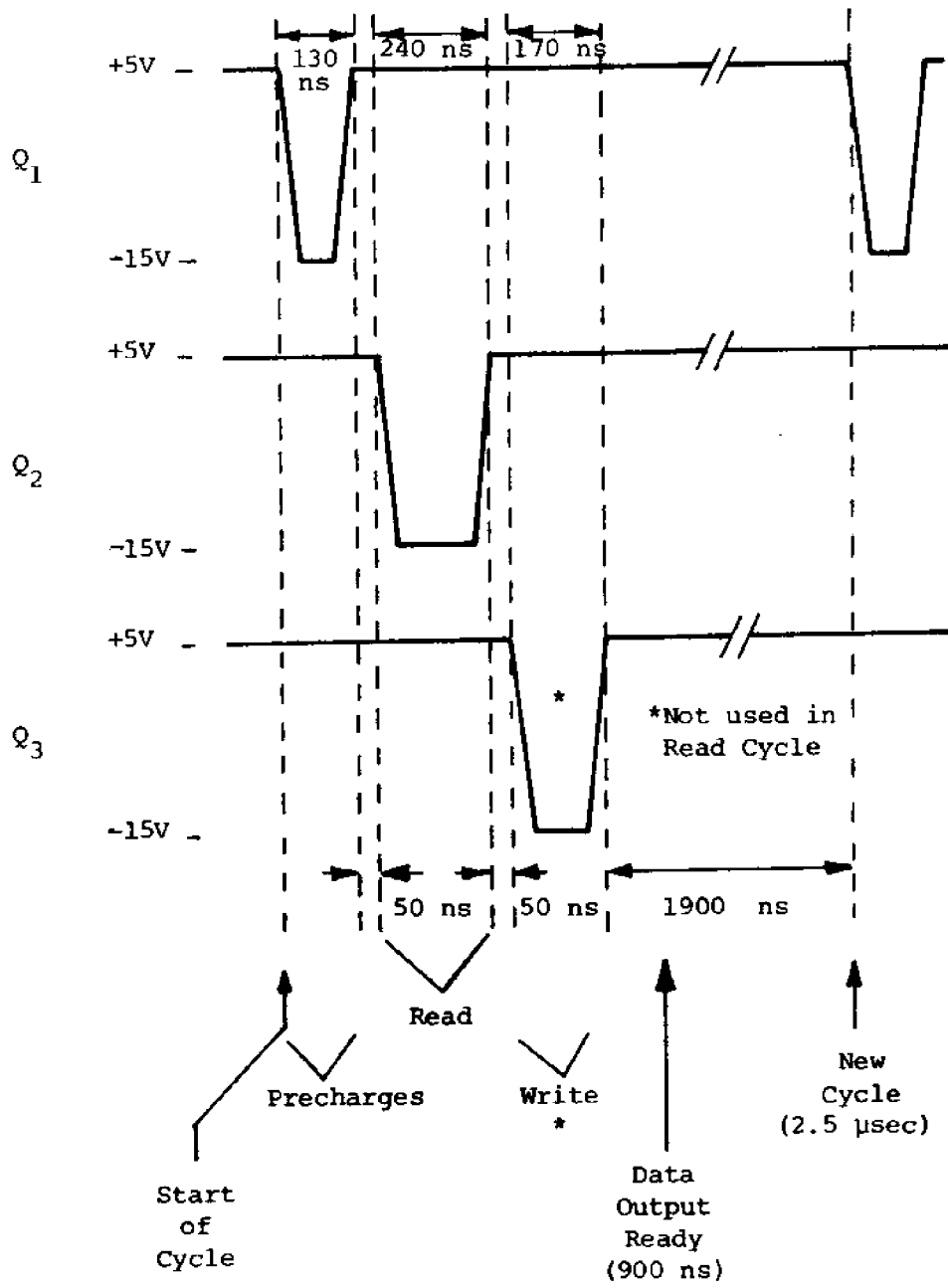


FIGURE 4.4 Clock Timing

Figure 4.3 shows the memory system architecture. The basic functions are to write data and to read it. To write into the memory, the CPU places the desired address on the A (address) lines, places the data to be written on the D (input) lines, and strobes (applies a pulse to) the "WRITE" control line. This stores the data. To read information, the CPU sets up the address lines, strobes the "READ" control line, and examines the data output on the Q-lines.

The memory chips are dynamic. This means that they store information as charge patterns on an array of very tiny capacitors. This charge will leak away with time (about 2 milliseconds) and must be periodically replenished. Thus, every 2 milliseconds or less, the memory must cycle through the low-order 5-bit addresses while the "REFRESH" control line is strobed. Inside the memory chips, this causes each bit to be read, and the value read to be rewritten, effecting replenishment. In the robot's computer, the CPU automatically performs this procedure.

To manipulate the charge patterns in the memory requires a significant amount of organized energy. This is provided by a three-phase high-power clocking scheme, Figure 4.4. These signals provide the energy needed to alter the memory cells, and their sequence and timing provide a reference for other signals in the system. Two of these timing signals are provided to the CPU, and coordinate exchanges between that and the memory. In the prototype, the basic period of these signals is 2.5 microseconds; thus 400,000 memory cycles per second are possible.

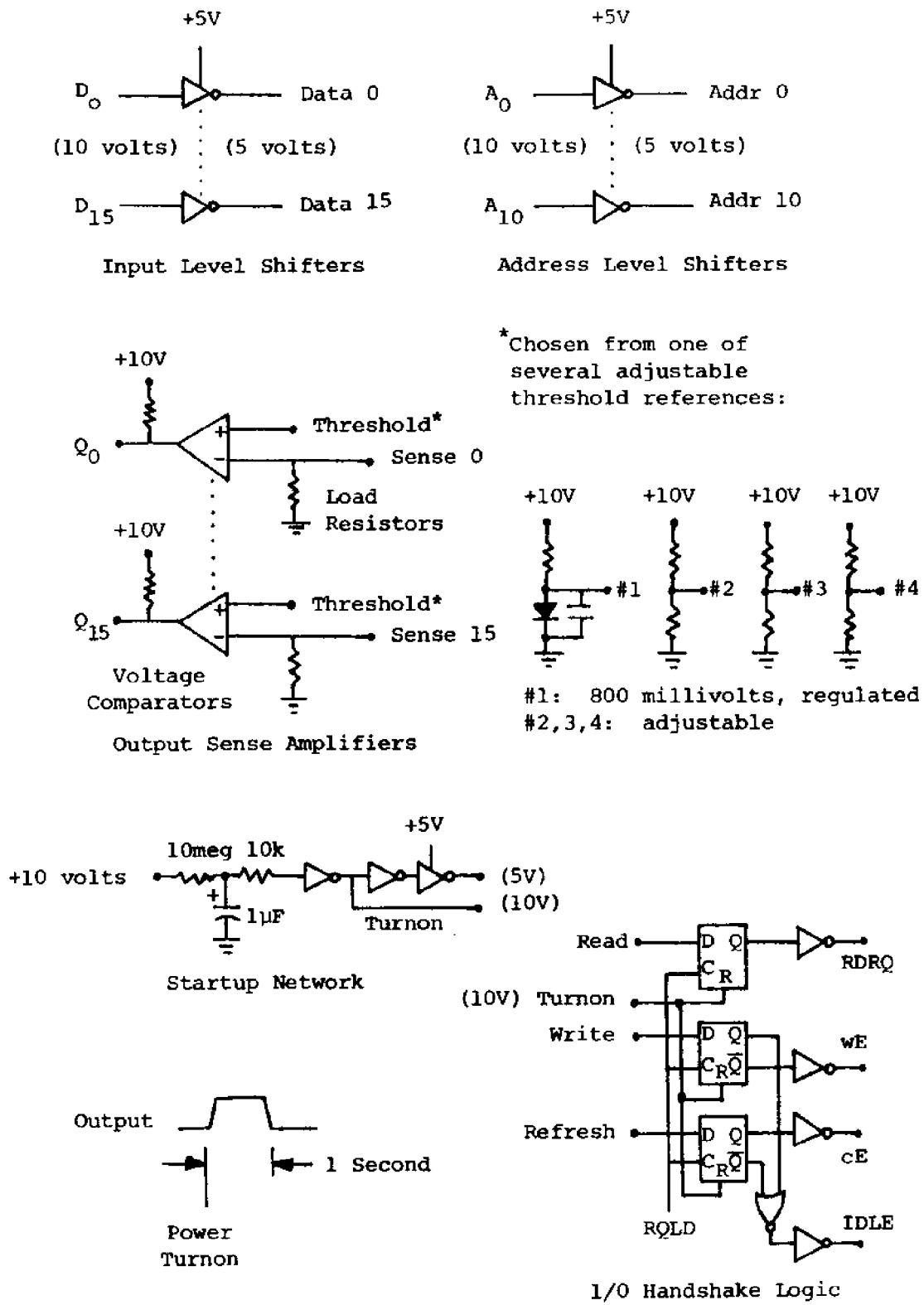


FIGURE 4.5 Memory Circuits

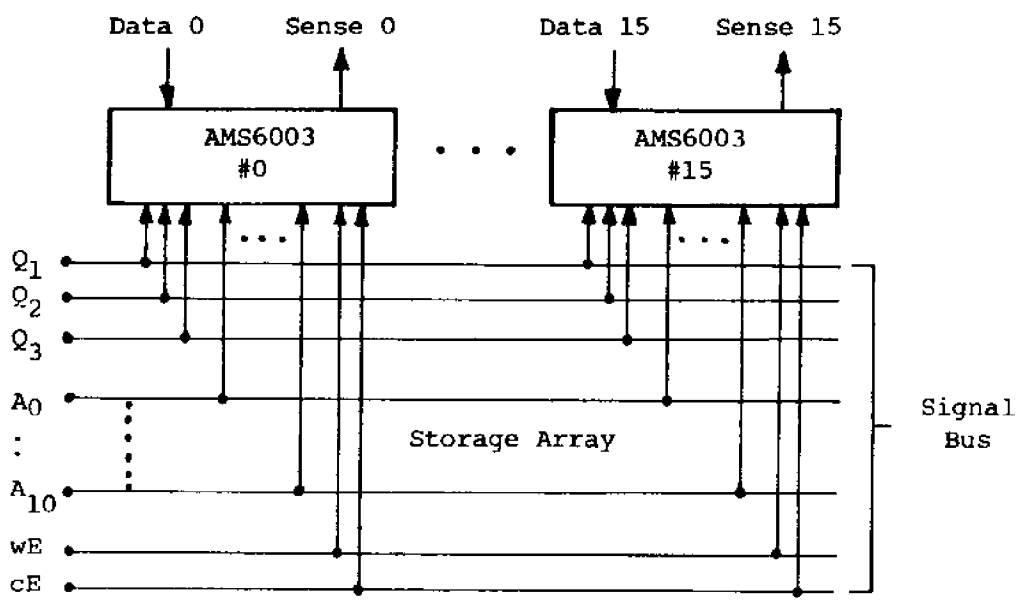
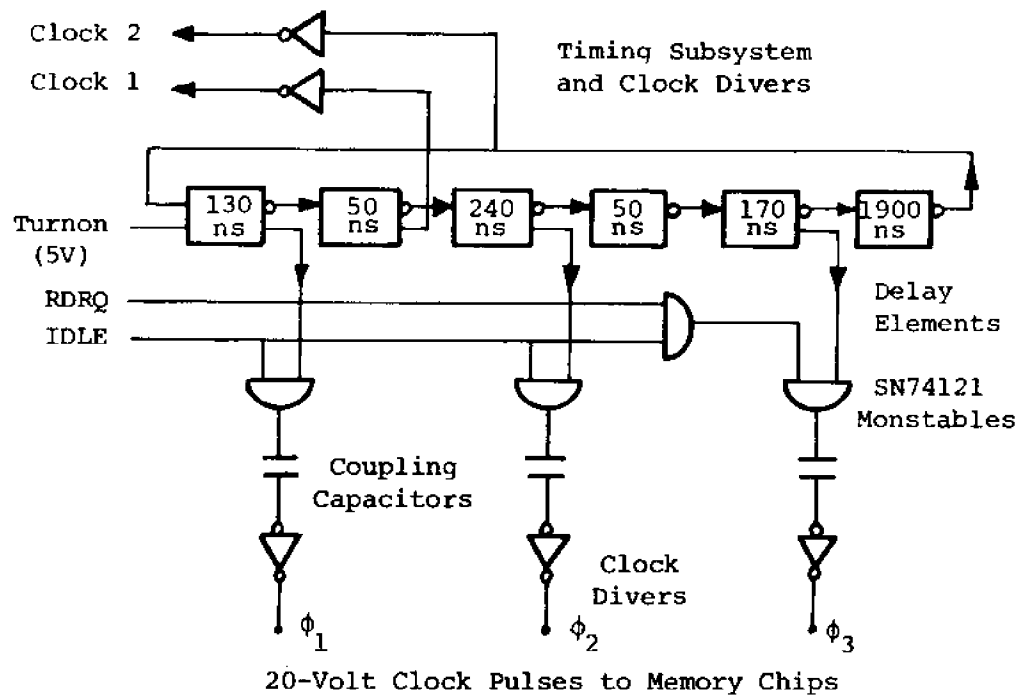


FIGURE 4.5 (cont.) Memory Circuit

A diagram of the memory is shown in Figure 4.5. Redundant circuits are diagrammed only twice. The function of the circuits are as follows:

INPUT AND ADDRESS LEVEL SHIFTERS: The CPU generates CMOS signals of 10-volt amplitude. The memory chips accept 5-volt signals. Thus, a conversion from 10- to 5-volt levels must be made between them.

I/O HANDSHAKE LOGIC: Accepts requests for read, write and refresh cycles from the CPU, and translates these requests into control signals understood by the memory chips and timing subsystem.

TIMING SUBSYSTEM: Provides the basic timing and sequencing of signals for the system.

CLOCK DRIVERS: Translate the low-power timing signals into high-power clocking signals for the memory chips.

STARTUP NETWORK: When the system is first turned on, the power supplies, etc., take a moment to stabilize. If operation were attempted during this period, unpredictable errors would occur. The startup network inhibits system operation for about 1 second after turnon.

OUTPUT SENSE AMPLIFIERS: The data outputs of the memory chips are modulated currents. These are converted into 10-volt-modulated CMOS signals by passing the current through load resistors, sensing the voltage drops with comparators, thresholds set inside the modulation range.

STORAGE ARRAY: The sixteen memory chips.

#### 4.2.2 Experimental Program

The memory was the last part of the computer to receive design attention. It was designed during the second and third weeks before departure for Castine. The parts were ordered, and trickled in during the final week. No breadboard was attempted; there was no time. The



memory was built during the first week at Castine. It was mostly debugged during the second and third weeks. Also during the third week a small memory tester was designed and built, to simulate the CPU should the latter not be ready in time. However, the CPU was ready and in the fourth week the CPU and memory were coupled. The remainder of the fourth week was spent "chasing glitches" in the combined system. On the night of the last working day in Castine, the system worked. The CPU was successfully storing and retrieving data in the memory, and performing operations upon the data.

The primary difficulties encountered were inductive coupling between the power supplies and the high-current clock lines, and resistive losses in the power supplies. The former was reduced to tolerable levels with the application of a large foil ground-plane to the circuit board. High-frequency bypass capacitors minimized resistive losses in the power supplies.

The power consumption of the memory and CPU together was about 6 watts.

#### 4.3 THE INPUT/OUTPUT INTERFACE

The interface is a device which enables the computer to communicate with the rest of the submarine circuitry; a flow chart is presented on Figure 4.6. Given a 16 bit digital command and a start pulse, it can read or write analog voltages on one of 64 lines or give depth, speed, or course instructions to the analog controller.

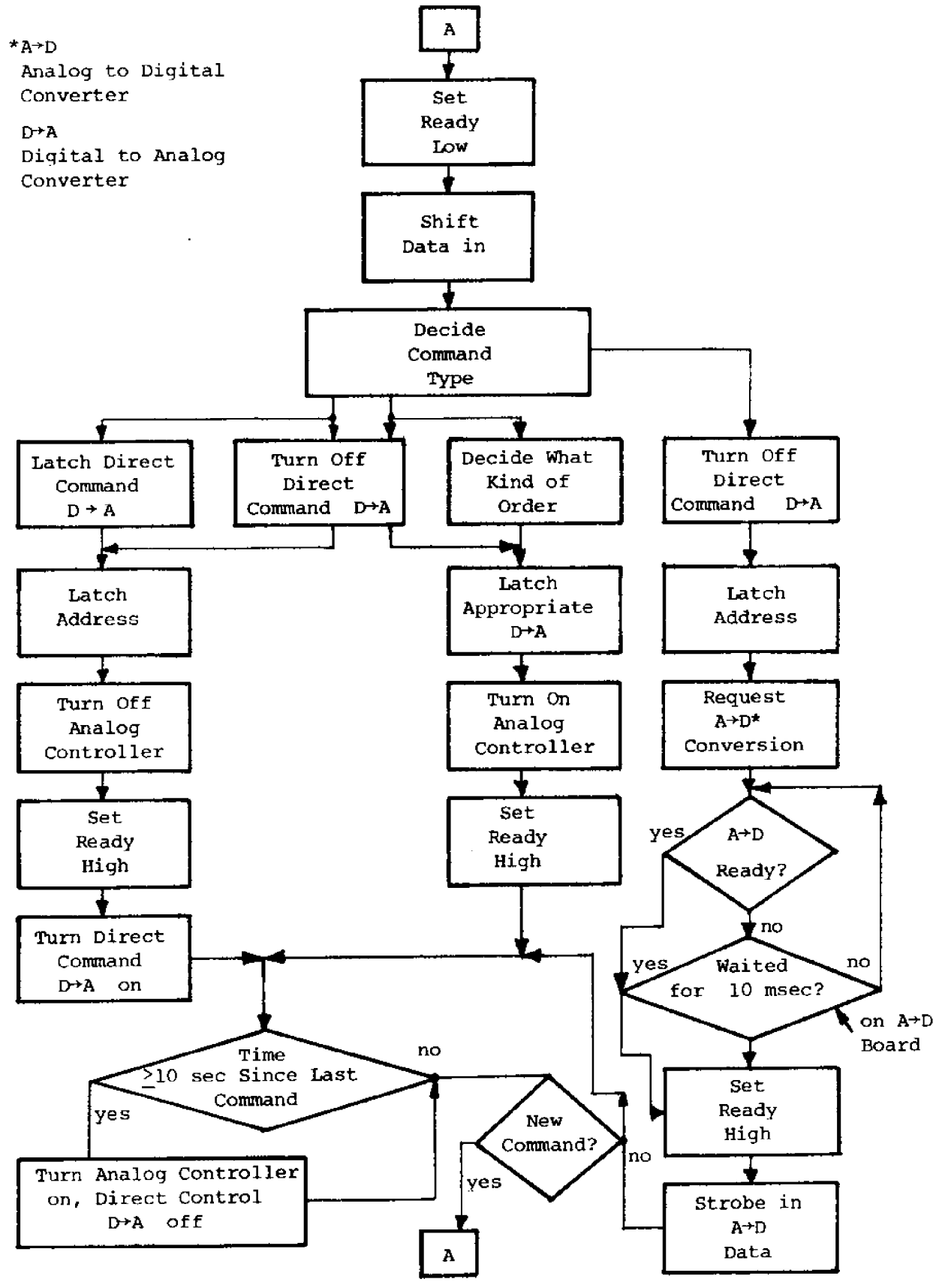


FIGURE 4.6 Interface Flow Chart

A major design consideration in designing the interface was holding the number of wires between the computer and the autopilot to a minimum. Two separate methods of doing this were used. The first was the use of serial data transmission to transfer the computer command to the autopilot and autopilot information to the computer. Serial transmission involves shifting data from one place to another, one bit at a time along a single wire. The second wire reducing method used was line multiplexing. A wire used as a data transfer line, for example, would be used at another time to indicate that the interface is ready for the next instruction.

The 16 bit command transmitted to the autopilot side of the interface is used in three sections. Bits 9 and 10 determine the command type, either a readout, order, or direct command. Bits 1-8 are digital data in order and direct commands, and bits 11-16 are an address used in all commands.

Given a readout command, the interface will connect one of 64 lines to the input to an analog to digital converter, request a conversion, and strobe the result into a shift register. The analog to digital converter takes a voltage between 2.25 and 7.75 volts and changes it to a binary number between 00,0000,0000 and 11,1111,1111. This result is sent back to the computer side of the interface on the next interface command.

There are three types of order command; course, depth, or speed determined by the address bits. A course or depth command will cause the 8 data bits to be stored and converted to a voltage between 2.25 and 7.75 volts. The speed command stores the 8 bits, and uses one bit for forward,

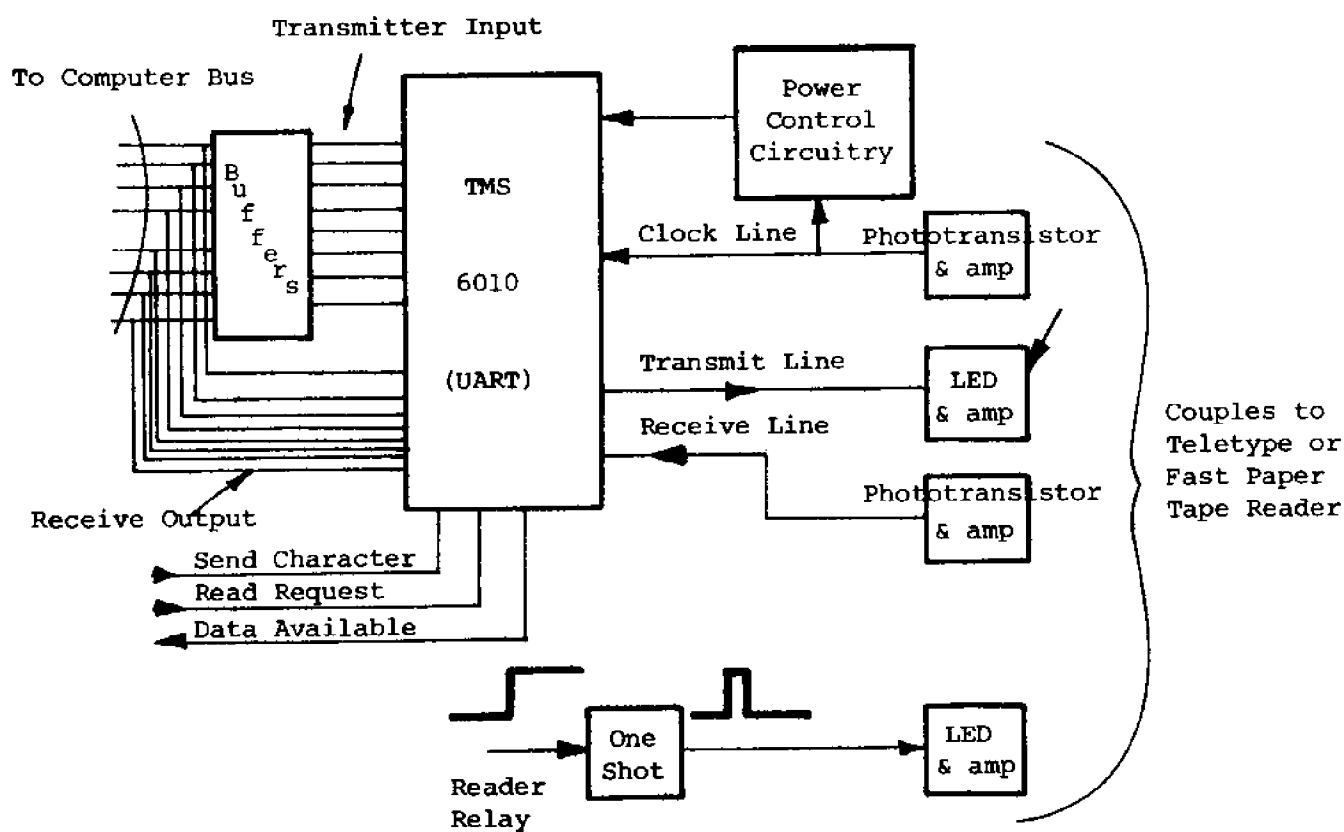


FIGURE 4.7 Teletype Interface on the Computer Side

one for reverse, and converts 4 to a voltage used for motor speed control; this is not yet implemented. All order signals go to the analog controller.

For a direct command, the interface stores the 8 data bits and converts them to an analog voltage. The digital to analog converter used for this task is separate from the 3 converters used to direct the analog controller. This output is then connected to one of 64 lines. By connecting some of the lines to the inputs to control surface servo amplifiers, this gives the submarine the capability of performing complicated maneuvers by having the computer control the rudder and fins directly.

Some of the problems encountered while debugging were with switching the line multiplexer connecting autopilot and computer, design of the on-off control for the analog controller, latching for speed, course, and depth, and varied timing problems. One of the problems remaining is that carbon resistors were used in the digital to analog converters, which will drift appreciably due to the temperature variation between lab and underwater operating conditions. These should be replaced with low drift precision resistors. It is also possible to make the interface more flexible by using a special order command to turn the analog controller on and off. Currently any direct command will turn the analog controller on, and any order command will turn it off.

#### 4.4 COMPUTER PERIPHERAL EQUIPMENT

##### 4.4.1 Teletype/Paper Tape Reader Interface

The teletype/paper tape reader interface provides 2 way communication between the computer and the teletype, and allows program loading with the fast paper tape reader, Figure 4.7, 4.8 and 4.9. Putting

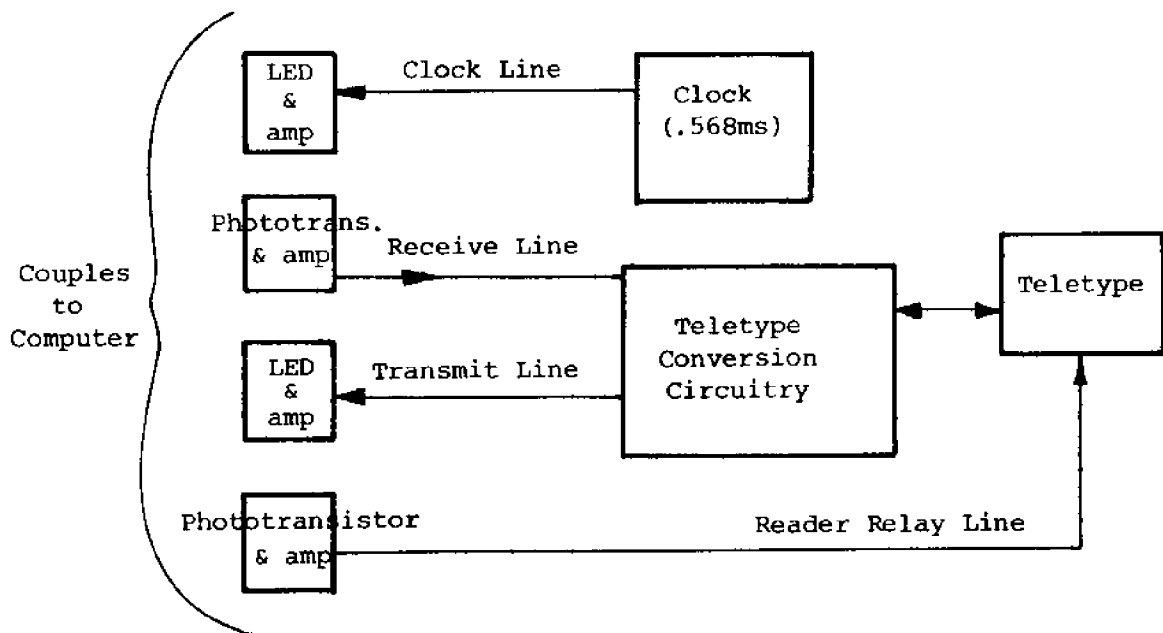


FIGURE 4.8 Teletype Interface

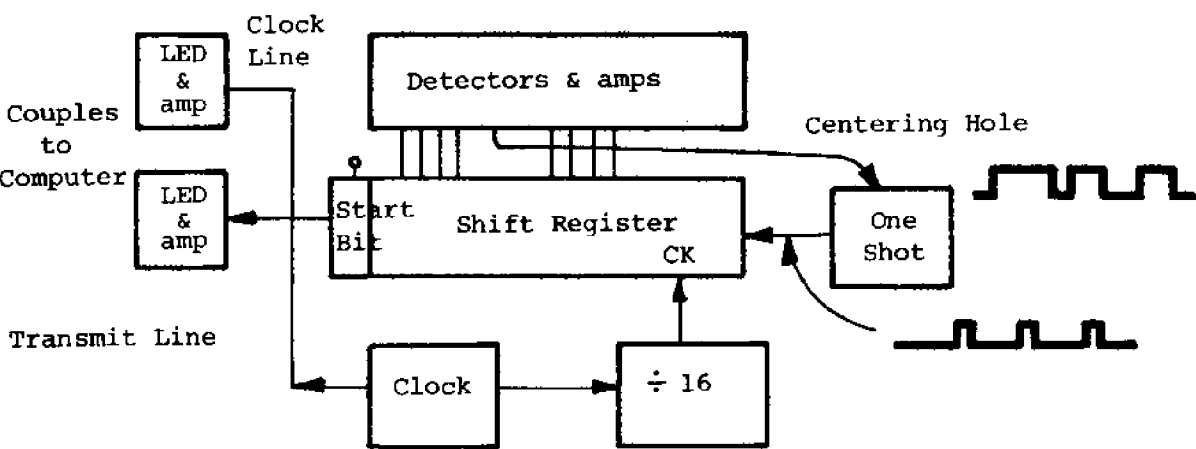


FIGURE 4.9 Fast Paper Tape Reader Interface

Electronics in the fast paper tape reader performs a similar function to the transmitting section of the UART, Figure 4.9. Holes in the paper tape are detected using two light bulbs and 9 phototransistors (8 data and 1 centering). On the falling edge of light output from the centering hole, a pulse is sent to the shift register which latches in the data from the other 8 holes. Starting on the next clock pulse the data is shifted out serially. A ninth data bit, a start bit, is added to make the output look like a teletype. The serial data transfer must be fast enough so that it is complete before the falling edge of the next centering hole.

The problem with this device was mainly in getting consistently accurate sensing of the holes in the paper tape. In addition, the coupling phototransistor on the clock input to the interface is just marginally fast enough for the fast tape reader clock. A faster transistor should probably be used. Problems were also encountered in the teletype conversion circuitry due to inadequate terminal description of the teletype.

#### 4.4.2 The Control Panel

The control panel is used to start up the computer, debug computer programs, and issue direct commands to the autopilot.

The problem was to design a data input system which would operate efficiently both in and out of the water. Two additional constraints, arising from the space available in the hatch, were a 2" depth limitation on the panel size, and a limit of 18 wires connecting the panel to the computer package.

the clock on the teletype/paper tape reader side of the interface makes the paper tape reader look to the computer like a very fast teletype, and thus completely compatible. Light emitting diode to phototransistor coupling is used to provide a method of communicating with the computer while keeping it waterproof.

The most important component in this interface is a Universal Asynchronous Receiver-Transmitter integrated circuit (UART). Given a pulse of the send character line, it sends the 8 bits on the computer bus out in a serial fashion on the transmit line at one-sixteenth the clock rate. The receive section of the UART recognizes a start bit from the teletype/papertape reader, changes the subsequent 8 bits of serial data to a parallel form (8 separate lines), and puts the data available line high. A read request signal will put this data onto the computer bus and reset the data available line.

The UART draws considerable power, (60 ma at 10 v and 10 ma at -12v). It is not operational when the submarine is in the water, so power control circuitry is used which supplies power to the UART only when clock pulses are coming in.

The reader relay line allows the computer to request one character at a time from the slow paper tape reader attached to the teletype. When the line is pulled high it sends a single pulse to the reader relay, which should cause the reader to send one character. The reader sends one character most of the time, but occasionally sends two, three, or more when given a single pulse.



Physically, the panel is 12-1/2" x 6" x 1-7/8". It consists of a block of PVC, 12-1/2" x 6" x 1" with milled channels of varying width and depth. A 1/2" thick piece of PVC is cemented under the area of the deepest channel, (7/8"), for extra support. A sheet of plexiglass, 12-1/2" x 6" x 3/16", covers the panel and is sealed with silicone rubber. Wherever possible, small pieces of PVC were cemented inside the panel to help support the plexiglass top against water pressure. Three waterproof 9-pin connectors, (two for the computer and one for the autopilot), are mounted in the bottom of the panel.

The type of switches used in the panel were small magnetic reed switches. They were normally open electrically until a magnet was placed directly over them. The switch then remained a closed circuit until the magnet was taken away. A programmer inputs data by placing magnets on the plexiglass top over the appropriate reed switches.

Thirty-four reed switches were mounted in the panel. The computer requires sixteen data switches, ten function switches, and an execute (XCT) switch. The remaining seven switches are connected directly to the autopilot. These can be used to bypass the computer entirely.

Due to the limit of 18 wires, the data and function switches could not be wired directly to the computer. A multiplexing scheme was devised to read these switches and send the information to the interface board in the computer package on only two wires, one for data and the other for functions. Multiplexing involves sampling several input lines and sending these samples over a single output line. Thus, the information

contained on the sixteen data lines can be multiplexed and sent on a single wire and the information from the ten function switches can be sent on another single wire to the interface board. Once at the interface board, the information is converted back into parallel form for use by the computer.

Also contained on the interface board was the circuitry which handled the data coming back from the computer. This data is multiplexed and sent to the panel where the display circuitry uses it to turn on the appropriate LED's (light-emitting diodes) which serve as panel lights.

The control circuitry in the panel supervises the operations performed. When the panel is not in use, the control circuitry is in the WAIT state. The main clock is running, but all panel lights are off to save power. When the XCT switch is closed, the control system cycles through INITIALIZE, where one pulse resets, counters and clears shift register, to CONSOLE OPERATE where the switches are read and the information is sent to the computer package. A "console operate done" pulse causes the control system to enter the DATA DISPLAY state, where data from the computer is displayed on the panel lights until the XCT switch is opened, allowing the programmer to display data for as long as he chooses. The opening of the XCT switch sends the system back into the WAIT state until the next cycle is started. If a command or data is sent to the computer but there will be no data coming back, the panel lights will display the state of the data input switches.

The biggest problem with the panel design concerns the limited sensitivity of the reed switches. Problems begin to arise when they are placed inside a PVC block and the only access to them is through a sheet

of plexiglass. If the plexiglass is too thick, or the switches have not been placed as close as possible to the underside of the plexiglass, the magnets cannot always cause the switches to close. If the plexiglass is too thin, however, it could not withstand much pressure. Stronger magnets are not necessarily a solution because the panel is constrained to be under a certain maximum size and the switches are placed only 3/8" apart in some cases, so a strong magnet could affect more than one switch at a time. Presently, the only solution is to try to keep the number of the switches needed to a minimum, so that they can be placed as far apart as possible within the panel, and the strongest possible magnets can be used.

#### 4.4.3 The Paper Tape Reader

The purpose was to provide a battery operated, portable, paper-tape reader to communicate with a computer contained in the robot submarine. The tape reader was built because of the unavailability of a device, of this description, on the market.

The tape reader uses a friction drive to run the punched paper tape over an optical sensing head. Light sensitive transistors are attached to the sensing head via fiber-optic light pipes. The transistors detect a row of holes, in the tape, at the same time. Digital logic converts the signals into serial form so that an optical link, to the computer, will have the minimum number of light couplings. The tape reader is splash resistant inside its plastic box. Included in the box is a 6 v lantern battery, which powers the device. The sensing head used two 3.5 v flash light bulbs in series to illuminate it. The sensing head consists of bundles of five, 20 mil light fibers which connect to light

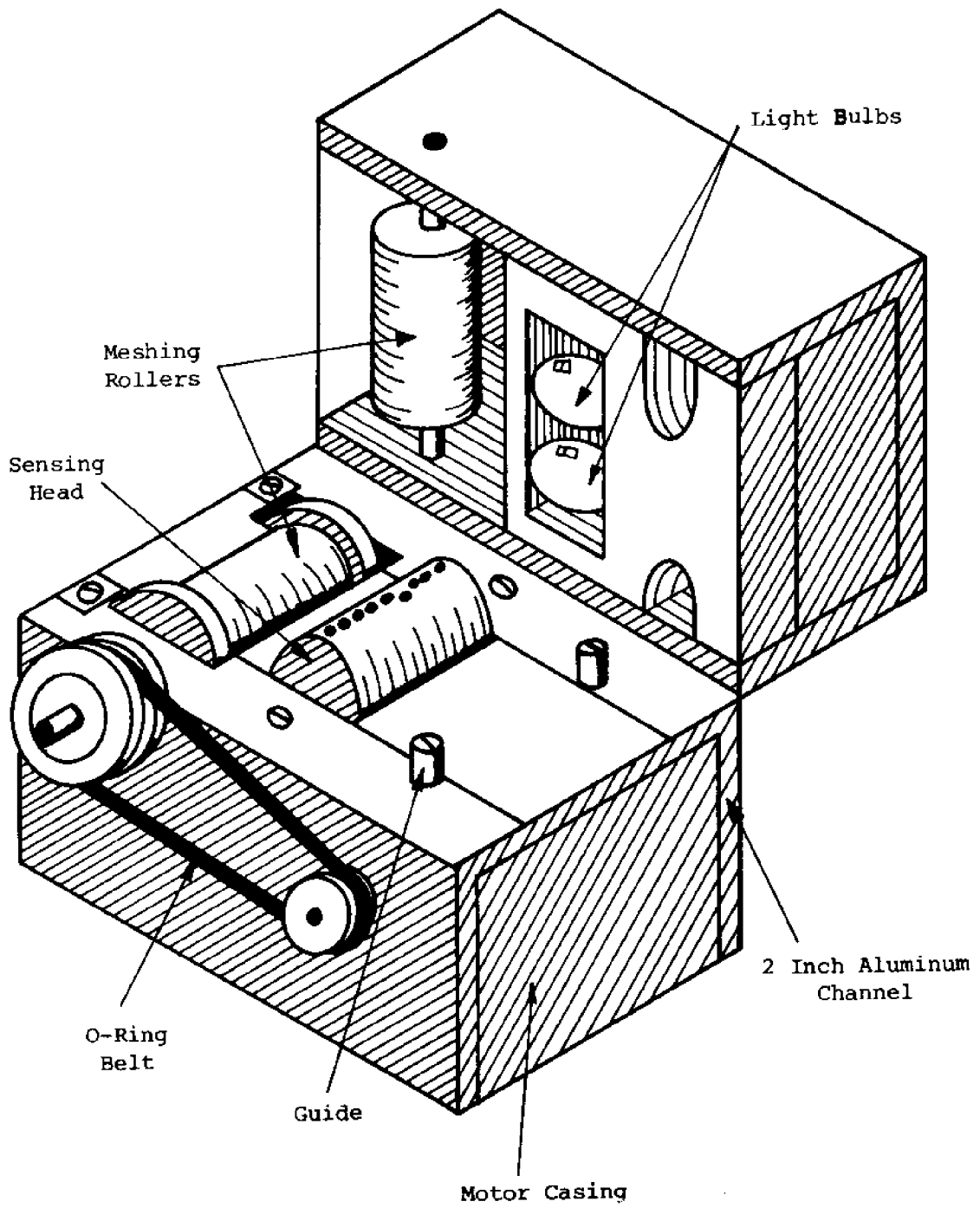


FIGURE 4.10 The Paper-Tape Reader

sensitive transistors. The frame of the light detecting assembly is machined out of PVC, Figure 4.10.

The motor is a good six volt model motor which runs at about 200 rpm with a 40 : 1 reduction box. The drive wheel uses an O-ring belt and the tape passes between two meshing rollers. The drive mechanism is mounted inside a piece of 2 inch aluminum channel, Figure 4.10.

Tests with the paper tape reader showed that the tape reader reads approximately 50 characters per second. The device draws 0.5 amps, which is mostly used by the light bulbs and motor.

The tape reader works but the following difficulties were encountered:

1. Pale colored paper tape does not read reliably because the paper transmits too much light and the contrast between a hole or no hole is very poor.
2. The O-ring drive slips if too much pressure is put on the top roller, consequently, the friction drive is not completely reliable and a snag in the tape will prevent the tape from reading.
3. The fiber optics could not be glued firmly enough to the aluminum and a separate rigid assembly had to be made to prevent any stress from being placed on the glue joints. It was found that white glue was the most effective glue because most other glues attacked the plastic light pipes.
4. The transistors gave varied outputs because light transmitted by each pathway varied. Individual transistor signals had to be amplified differently to give similar outputs.

Recommendations for improvements are:

1. A chain drive would transmit more torque than the O-ring drive.

2. Greater pressure on the upper roller would make the friction drive more reliable but this could only be implemented after a chain drive has replaced the O-ring drive.
3. A bright but diffuse light source would cause all light pathways to be approximately equal.

#### 4.5 COMPUTER SOFTWARE

Software developed for the mini-computer includes a bootstrap loader, an absolute loader, an assembler, memory tester, and simple path-maker/follower routines to guide the submersible. These programs were all developed before the minicomputer was built, compiled and debugged on a PDP-11 computer using a cross-assembler which translates robot assembly language to PDP-11 assembly language.

In order to load programs into the computer, the bootstrap loader is first "toggled" into any 25 consecutive locations by means of switches on the panel. This simple loader accepts binary tapes punched in "location, contents" format, where the first word (two 8 bit bytes) indicates an address and the second word specifies the contents for that location. The bootstrap loader exists solely to enable the much longer (75 word) absolute loader to be loaded into core via punched tape. Once the absolute loader is in core, the locations containing the bootstrap routine may be overwritten by other programs.

The absolute loader is block-oriented with error-checking capability and resides in high core. It automatically starts the loading program at a specified location and will not allow a user program to overwrite the loader itself. The assembler produces specially formatted binary blocks of code for the loader to place in core.

Binary coded blocks of up to 34 words are "assembled" from the mnemonic source code. The first byte of each block is the number of data words in the block. A word count greater than  $77_8$  indicates that the block is the last one on the tape and contains no data, only the address, in bytes three and four, at which program execution is to start. The second byte is the arithmetic sum of all following bytes, truncated to eight bits. The third and fourth bytes hold the beginning location at which data is to be stored or, as noted above, the transfer address to start the program just loaded.

There are fifty assembly language instructions. Alphanumeric symbols are limited to six characters of which the first must be alphabetic. Numbers are written in octal notation, providing a signed integer range of 0 to  $\pm 7777_8$ . Source statements are written in the form:

LABEL: OPERATOR OPERAND; COMMENT

with optional label and comment fields. Some operator instructions do not require an operand since they operate only on the accumulator.

There are three instruction (operator) types. Memory reference instructions include all those which operate on either data in core, the base register, or the program counter (PC). The accumulator/carry/skip instructions operate on the contents of the accumulator (AC), the carry bit or the skip field. Skip instructions cause the next sequential program step to be skipped if the condition specified by the instruction is met. Input/output (I/O) instructions, as well as allowing information flow to and from core via the AC, also manipulate external I/O device "flag" which indicate the current state of the devices.

I/O instructions must specify both the operation code and a device number (128 devices are allowed). Memory reference instructions specify the op-code, address mode and address. Four address modes allow the 8-bit address field to be treated as an absolute (octal) number, an absolute address in core, a displacement ( $\pm 128$  locations) from the current value of the PC, or as the address of a location whose contents are the actual address (indirect addressing).

Six assembler pseudo-operators are also provided. These instructions are used to initialize the internal registers, indicate end-of-tape, skip to a new page of listing, etc. Symbol values can be assigned directly with the following format:

SYMBOL = value; COMMENT.

The ASCII source tape is read into the assembler three times. Pass 1 generates an internal symbol table which assigns values (location numbers) to all symbols specified in the program. Pass 2 generates the block-oriented binary tape for the absolute loader. Pass 3 generates a listing of both the source code and the assembled machine code. The assembler will indicate seven types of programmer/machine errors. Execution will be suppressed if errors are noted.

Further software development includes an editor, program debugger and high level language compiler. The current instruction set is not firm and changes are expected as core size increases and new hardware becomes available.



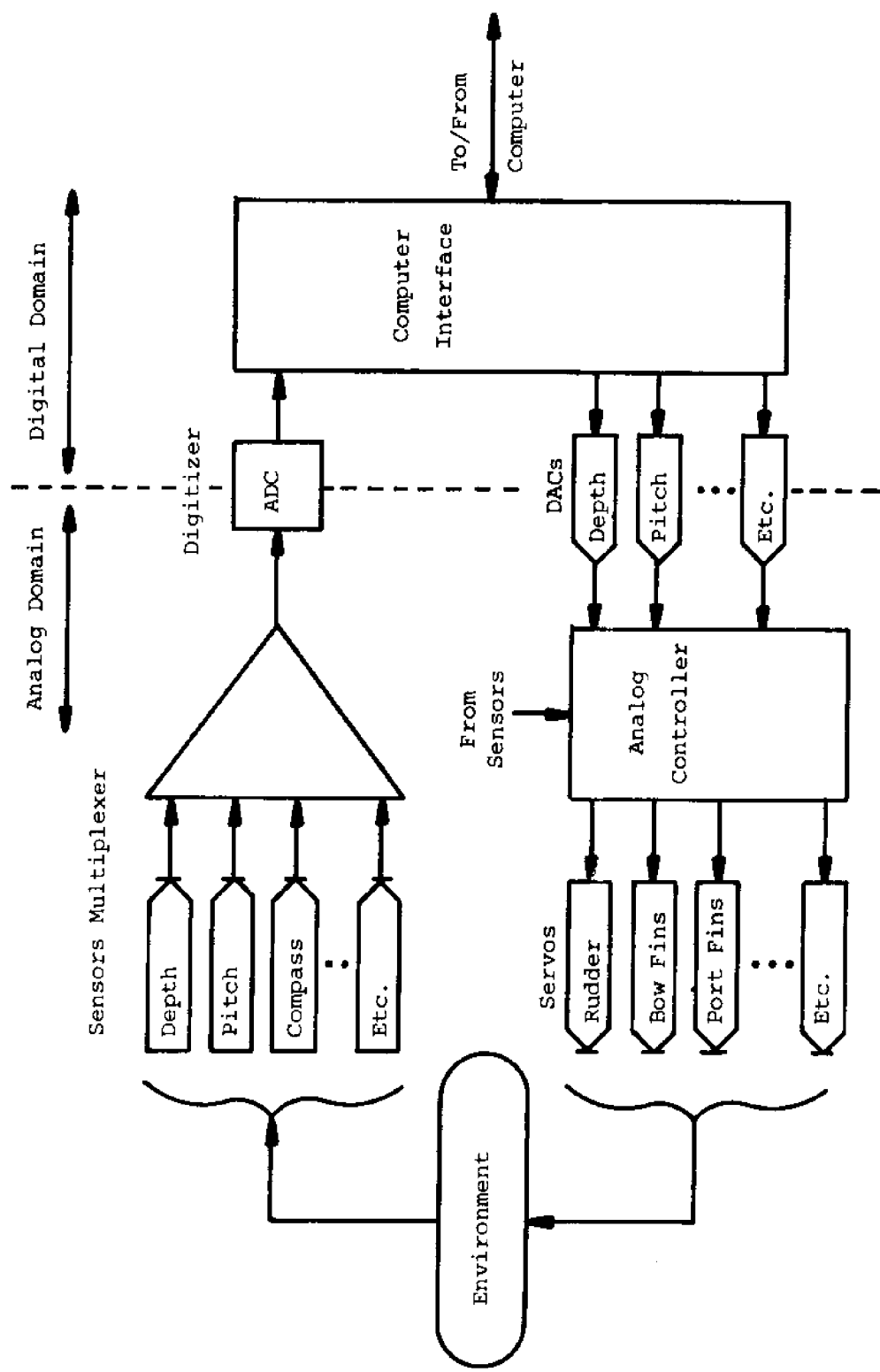


FIGURE 5.1 The Closed-Loop Control System (Autopilot)

## 5. THE AUTOPILOT AND SENSORS

When programmed for a specific course, the underwater robot could in principle follow that course using the digital computer to set and adjust the control surfaces. However, in practice such computer control modes have not been well developed. It was decided, therefore, to design an autopilot for the stable control of the vehicle with the computer to provide depth and course inputs when changes were called for. The computer would also monitor the depth, attitude, and course of the vehicle in order to be able to override the autopilot should this be required.

The autopilot, Figure 5.1, consists of various sensors producing analog signals, a multiplexer to select which sensor is read, and analog-to-digital converter (ADC) to digitize the sensor reading, a digital interface to exchange data and control signals with the computer, and digital to analog converters (DAC) to convert computer commands into analog form for the analog controller/servo amplifier subsystems.

### 5.1 THE AUTOPILOT

#### 5.1.1 The Controller Arrangement

The control of heading is rather a simple process since it is sensed by the compass and the control movement is applied to the rudder. The control of depth, roll, and pitch are more complicated because the control forces are together applied by the diving planes. There is therefore coupling in the controller of these actions. Depth is maintained by the combined action of the bow and stern diving planes, roll is controlled by the differential movement of the two stern diving planes, while pitch is controlled by the differential movement of the bow and stern diving planes.

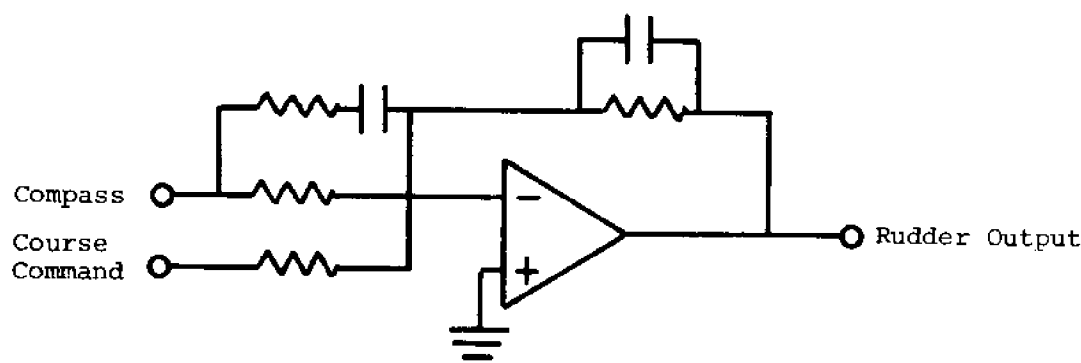


FIGURE 5.2 Basic Controller Circuit

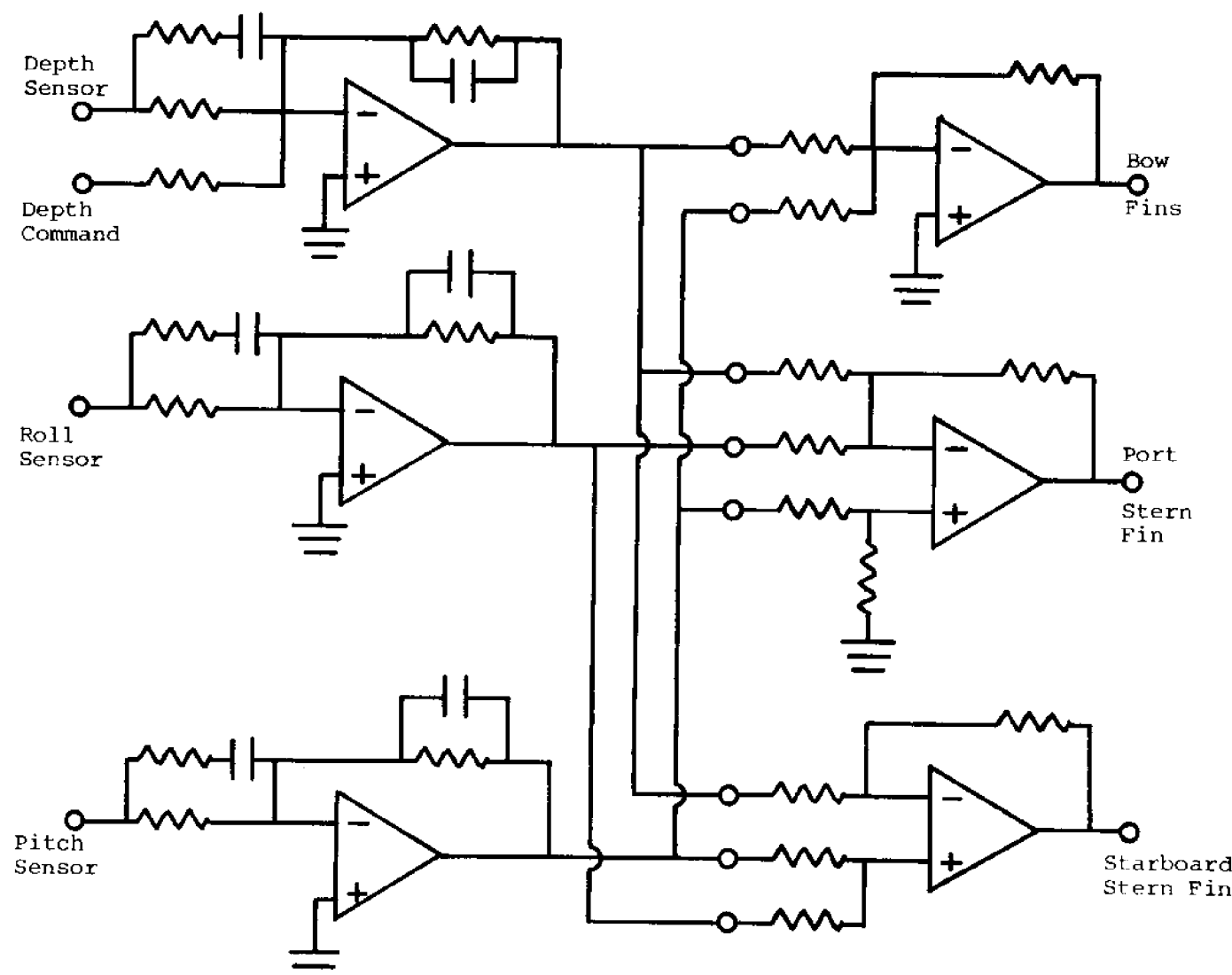


FIGURE 5.3 Controller Circuit for Dive Planes

The basic circuit to implement the control functions is shown in Figure 5.2. This arrangement provides the desired proportional plus differential correction signal and in addition high frequency noise is filtered out. The basic circuit is used for the heading control where the desired and actual headings are the input signals and the output goes to the rudder servo amplifier, as in Figure 5.2. The depth control is combined with the pitch, and roll controls to operate the servo amplifiers for the diving planes, Figure 5.3. With this arrangement the depth is the control command while the roll and pitch angles are sensed and controlled.

#### 5.1.2 The Servo Amplifiers

The servo amplifiers provide the power to drive the servomotors which in turn operate the rudder and the diving planes. The controller described above provides in analog form the required settings of the control surfaces. The required settings are compared with the actual settings as measured by the position potentiometer in the servomotor and output from the relays operates the servomotors, as shown in Figure 5.4. The basic problem with the circuit is the tendency to servo oscillation. With the servomotor not attached to the control surface (i.e. with no load) the capacitor in the feedback circuit was critical. A large value capacitor caused lag in response which encouraged low frequency motor vibrations while a small value let through noise which caused relay chatter. These problems were not observed when the servomotors were connected to the control surfaces, although they might have been present.

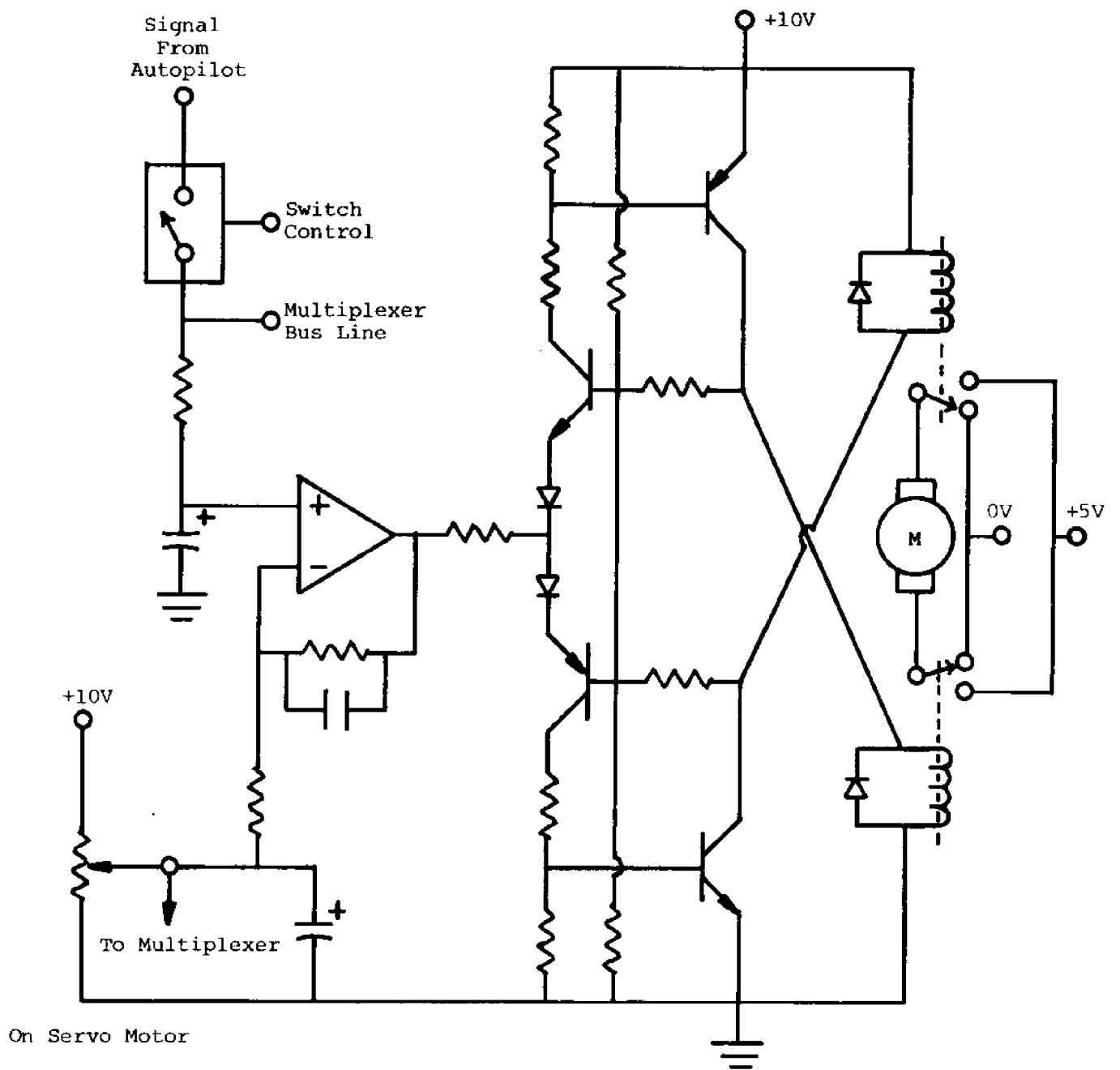


FIGURE 5.4 Servo Amplifier Circuits

### 5.1.3 The Analog to Digital Converter

The purpose of the ADC (analog-to-digital converter) is to provide a 10-bit CMOS-compatible digital code representing the analog signal from the sensors. The range of the sensor outputs (ADC input) is 5.5 volts, from 2.25 to 7.75 volts. The output code is inverse binary, the most significant bit (MSB) having a weighting of  $1/2$  the full scale range, the next bit  $1/4$  f.s., and so on through the least significant bit (LSB) with a weighting of  $1/1024$  of full scale. Thus, the smallest count is 0, the largest  $2^{10}-1$ , representing a range of 2.25 to 7.75 volts resolved into 1024 parts. When calibrated, a 10-bit ADC is accurate to within 0.1% of full scale.

Several constraints affected the design of the converter.

1. Stability: should remain accurate under thermal stress.
2. Power consumption: preferably less than 20 milliwatts.
3. Speed: should require no greater than 1 millisecond to convert.
4. Size: should not exceed 30 integrated circuits.
5. Costs: should be under \$100.

No commercial units met all of these constraints. The few with under 20 milliwatts consumption cost well over \$200.

The choice of conversion technique was straightforward once the requirements and constraints were defined. Parallel-conversion schemes are impractical for 10-bit precision. Dual-slope integrating types are too slow. Tracking types consume too much power, due to the need to operate continuously. Ramped-counter types either consume too much power or are slow. The method selected was that of successive approximations.

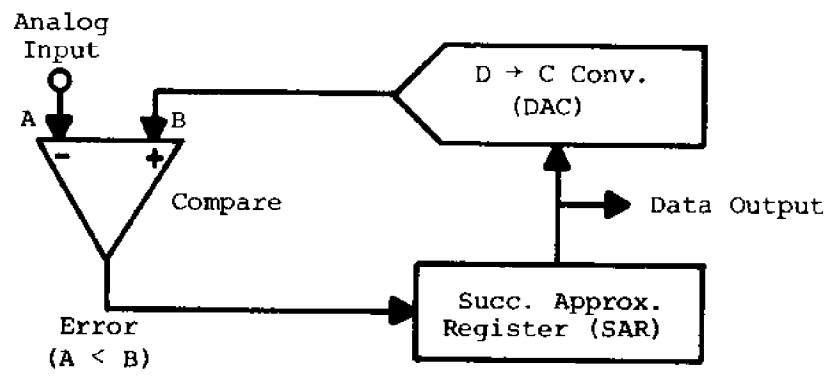


FIGURE 5.5 Structure of a Successive-Approximations A to D Converter

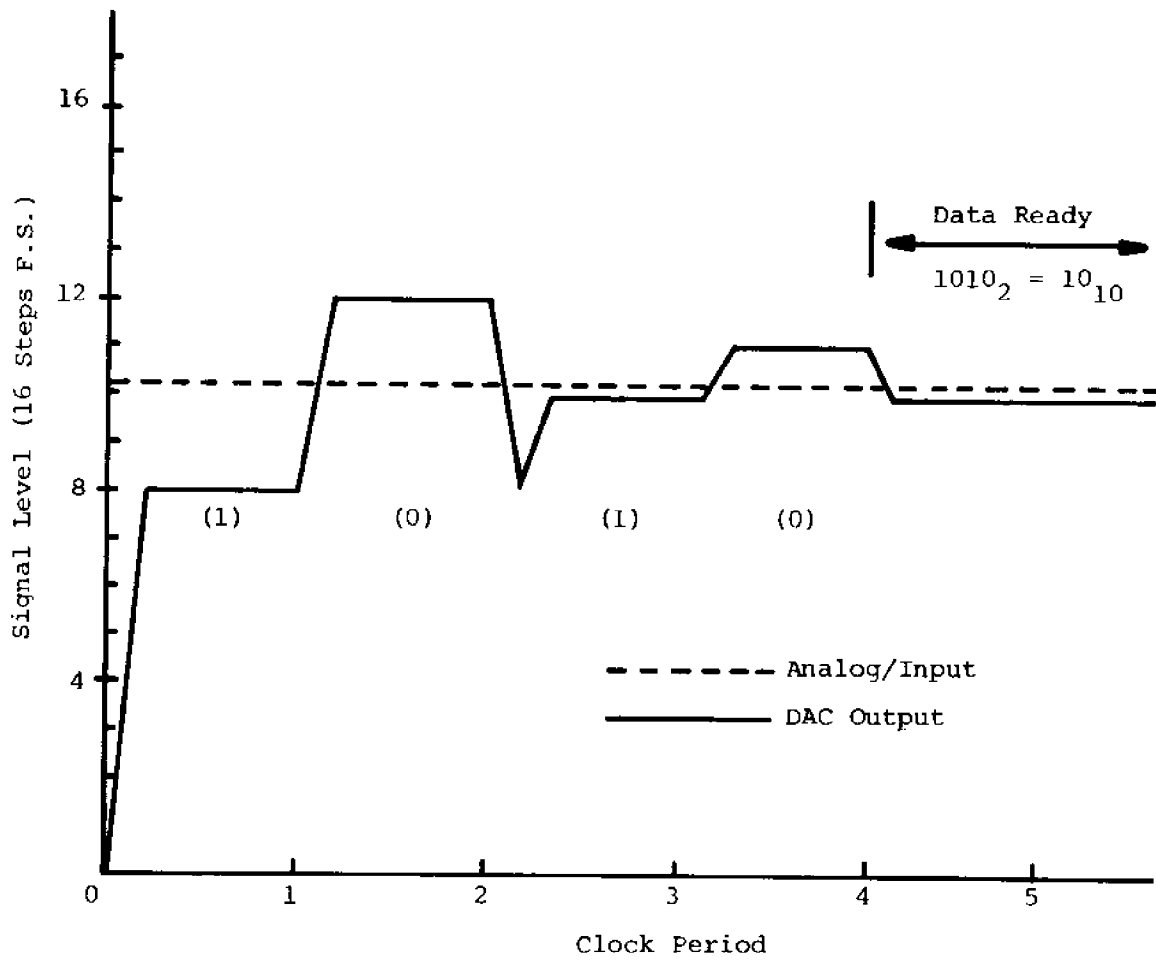


FIGURE 5.6 The Method of Successive Approximations

The method of successive approximations works as follows. The converter consists of a code generator (successive-approximations register or SAR), a digital-to-analog converter (DAC) to translate the SAR output into analog form, and a comparator which compares the DAC output with the analog input, generating an error signal if the former exceeds the latter, Figure 5.5. The SAR first tests the most significant bit (MSB). Should the resulting DAC output be lower than the analog input, no error signal is generated, and the SAR retains that bit on its output. Otherwise an error signal is generated, the MSB is rejected, and the next bit is tested. And so on, rejecting bits for which error signals are generated, until all bits have been tested. The DAC output then nearly matches the analog input, and the SAR output digitally represents the input. Figure 5.6 illustrates this sequence for a 4-bit converter.

The basic elements of the converter having been defined, the next design phase involved developing circuits for these elements. The choice of comparator was straightforward; the LM339 interfaces easily with CMOS, consumes little power and is quite fast. The choice of DAC required more thought. No low-power commercial units were available at reasonable cost. One could be built quite cheaply from resistor networks, though. A weighted-current network would have been thermally unstable; thus an R-2R type of network was chosen, which drifts very little with temperature.

The design of the SAR posed the main problem. A prototype using available CMOS components was breadboarded and debugged. A 10-bit implementation of this SAR would have required 17 integrated circuits (ICs). But later monolithic SARs became available, allowing a redesign requiring



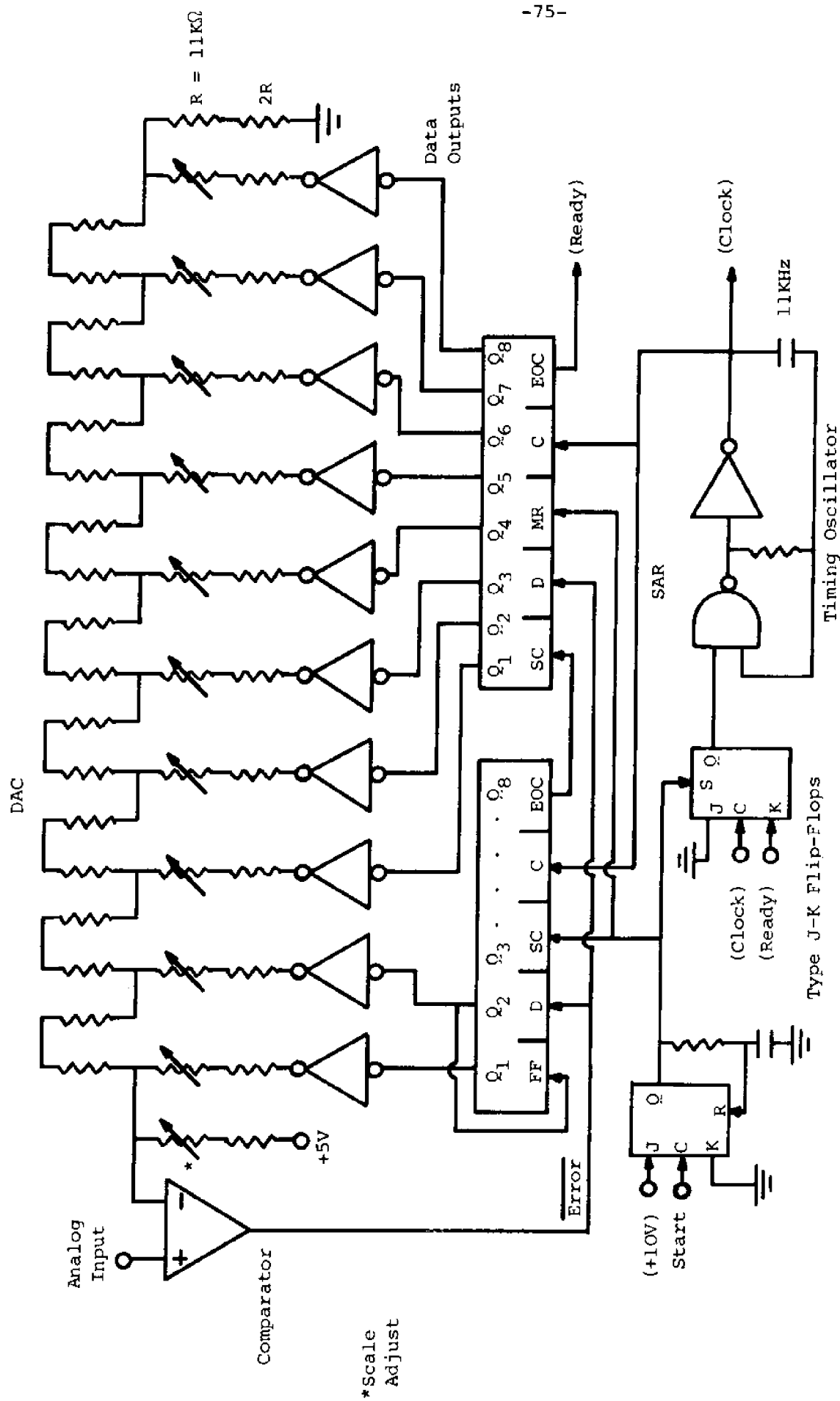


FIGURE 5.7 The Second and Final ADC Design

only 4 ICs. This new design was breadboarded and debugged as is shown in Figure 5.7, as part of a complete converter.

## 5.2 SENSOR DESIGN AND DEVELOPMENT

In order to maintain control of the submersible vehicle, sensors were needed to provide depth, roll angle, pitch angle and heading angle information in a form compatible with both the analog controller and analog-to-digital converter circuits.

A National Semiconductor absolute pressure transducer proved adequate for depth measurement. Four separate techniques for determining pitch and roll were investigated. One pitch sensor and two roll sensors each based on a different principle of operation were constructed and laboratory tested. A compass with an analog output was also constructed.

### 5.2.1 Design Criteria

Initial design criteria for specific sensors were as follows:

<u>Sensor</u>	<u>Range</u>	<u>Accuracy</u> <sup>1</sup>
Depth	0 - 200 ft.	1 ft.
Roll	+ 40 degrees	2 degrees
Pitch	+ 20 degrees	1 degree
Compass	0 - 360 degrees	2 degrees

Based on an average submersible speed of 5 feet/second, each sensor (except the compass) was required to respond to attitude changes, within individual accuracy limitations, in less than 200 milliseconds,

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<sup>1</sup> Including temperature effects over 0 - 50 degree range.

during which time the submersible would have traveled 1 foot. Power consumption was limited to 100 milliwatts per device, drawn from either 5 volt or 10 volt regulated ( $\pm 1\%$ ) onboard supplies.

If possible, the pitch and roll sensors were to be located in the autopilot tube. This requirement would limit the space available for both devices to a cylinder 6 inches in diameter and 2 inches deep. Location of the depth sensor was not critical; however, no hydraulic penetrations were desired through the autopilot housing as the enclosed circuits could be severely damaged by even slight salt-water leakage.

#### 5.2.2 Depth Sensor

The main component of the depth sensor was a National Semiconductor absolute pressure transducer. This transducer operates over a 0 to 60 psia range with a maximum allowable overpressure of 100 psia. Thus, the transducer has a depth capability of approximately 100 feet in seawater.

The transducer includes a transducer chip consisting of a Wheatstone bridge arrangement of four piezoresistors diffused into a silicon chip 1 mil thick which acts as the pressure diaphragm. This chip is laminated to a ceramic substrate measuring 0.750 by 0.820 inches which also contains temperature-compensating diodes, laser trimmed bridge-balancing resistors, a zener power supply regulator and one or two operational amplifiers.

The transducer could not be connected directly to seawater because of corrosion so that the inlet port of the pressure transducer was coupled to a neoprene rubber air bladder with a volume of approximately 15 cc. The bladder was located immediately forward of the bow bulkhead within the nose cone of the submersible.

Tank tests in freshwater indicated that the sensor was able to detect depth changes of 3 inches without temperature compensation. This was considered more than adequate and well within initial design criteria.

Figure 5.8 illustrates the simple attenuator circuit necessary to convert transducer output voltages to autopilot input levels. With a transducer excitation voltage of 10, the output signal was 54 millivolts/foot depth in saltwater with an initial value of 3.67 V at the surface. This response was attenuated and passed through a unity gain operational amplifier to produce an input signal compatible with the autopilot span of 2.25 V at the surface to 5.0 V at a depth of 100 feet. Resistors R2 and R3 can be varied to compensate for various water densities, allowing accurate depth measurements in both salt and freshwater.

Because of its very small size, it was possible to place the depth sensor in the multi-sensor package described later.

#### 5.2.3 Pitch and Roll Sensor Development

Pitch and roll information were desired in the form of angular deviations from a fixed "level" attitude determined by submersible ballasting. It was hoped that one method could be found which would allow construction of two identical devices, one oriented along the radial axis of the submersible and the second perpendicular to this axis, yielding pitch and roll information respectively. This duplication would facilitate construction and circuit design, as well as allowing interchangeability should one sensor be damaged during handling or assembly.

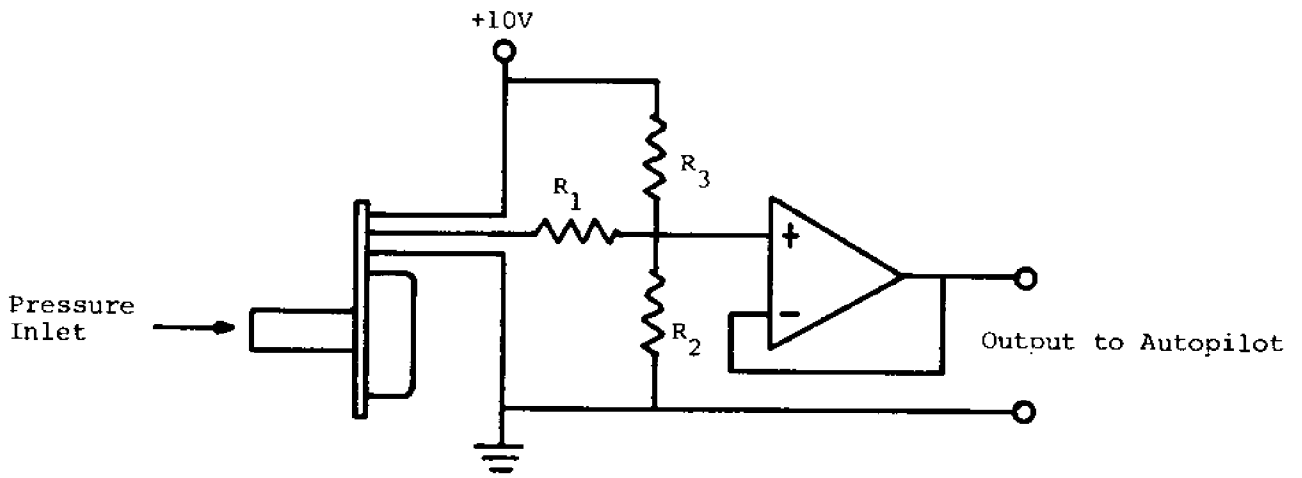


FIGURE 5.8 Depth Sensor Circuit

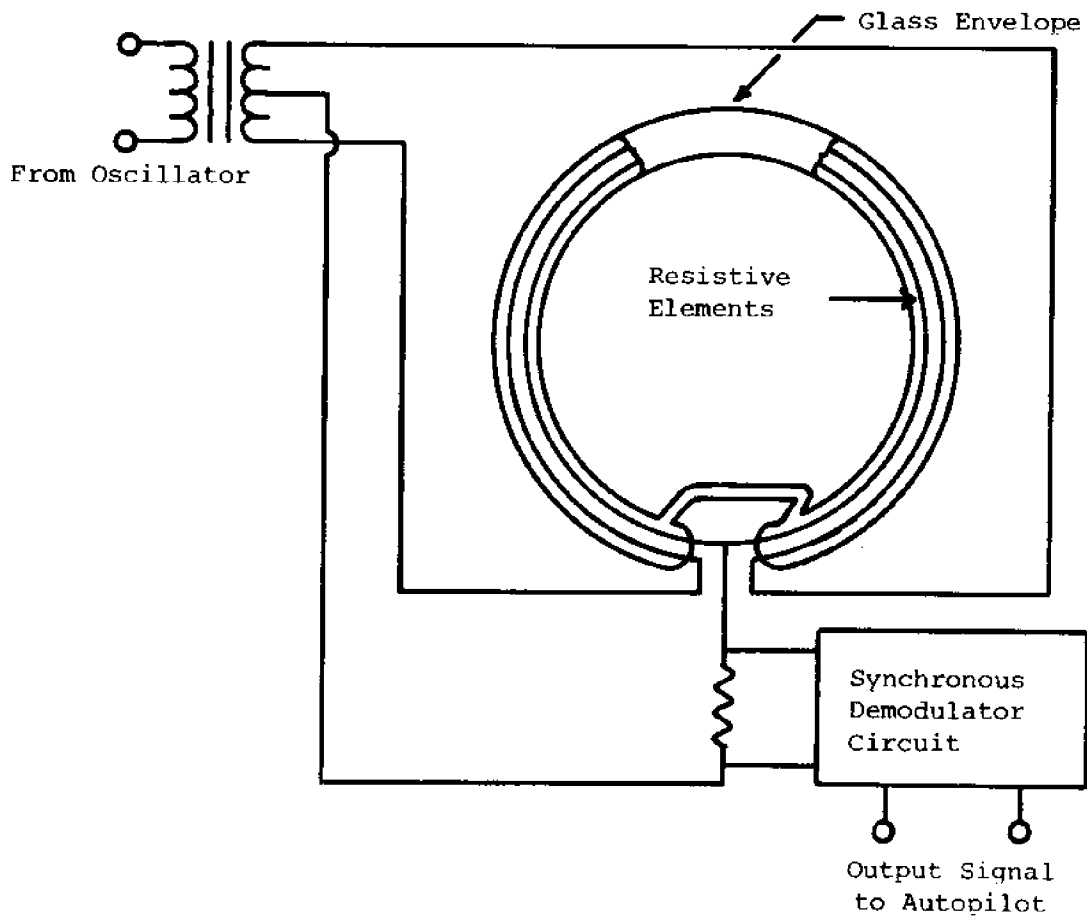


FIGURE 5.9 Electrolytic Roll Sensor

Following a review of current literature on transducers and inclinometers, three attitude sensing techniques were chosen for further parallel development. The three methods employed the following devices: a fluid-filled U-tube, a pendulum operated potentiometer and a differential pressure transducer. One working sensor was constructed using each technique and all three sensors were mounted in the submersible. These devices are described in the following sections.

#### 5.2.3.1 Electrolytic Roll Sensor

A fluid-filled U-tube lends itself well to measuring inclination. Rotation of the U-tube in its own plane causes fluid to rise above initial level in one arm and fall in the other arm. With the addition of resistive elements in each arm, the change in fluid level can serve as a variable resistor.

Initial experiments with this technique employed a mercury filled, 6 millimeter inside diameter glass U-tube with both Chromel wire and carbon rod resistive elements. This approach was later abandoned for the following reasons:

1. Mercury contamination can be extremely hazardous to both human experimentors and the aluminum skin of the submersible.
2. Electrolyzed deposits accumulated on the resistive elements, destroying the linearity of the variable resistance effect.

The second attempt used a commercially available electrolytic transducer, shown in Figure 5.9. In this approach a 1000 Hz oscillator induced an a.c. current in the resistive elements. Rotation of the sensor

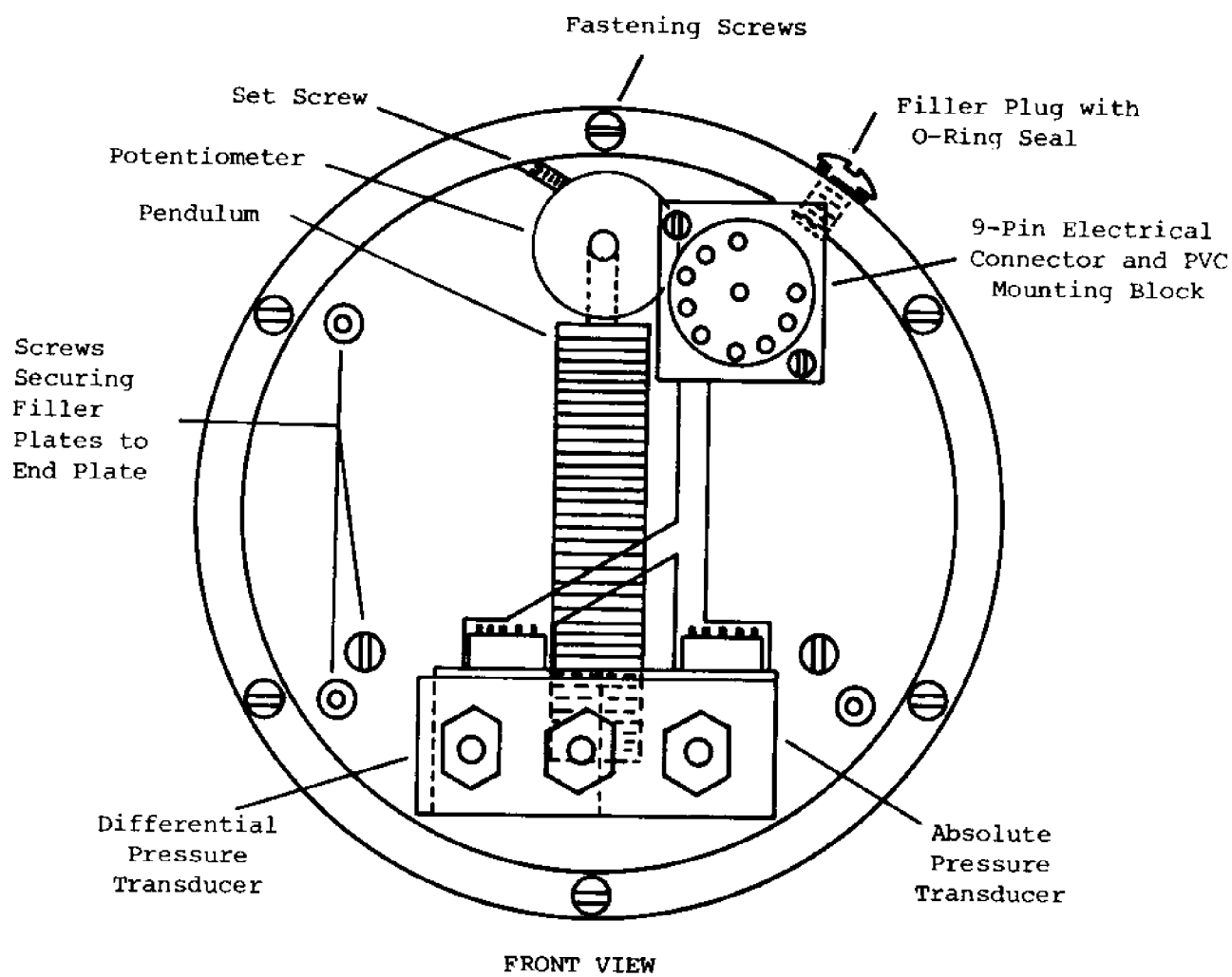


FIGURE 5.10 Front View of Multi-Sensor Package Showing External Location of Pressure and Electrical Connections

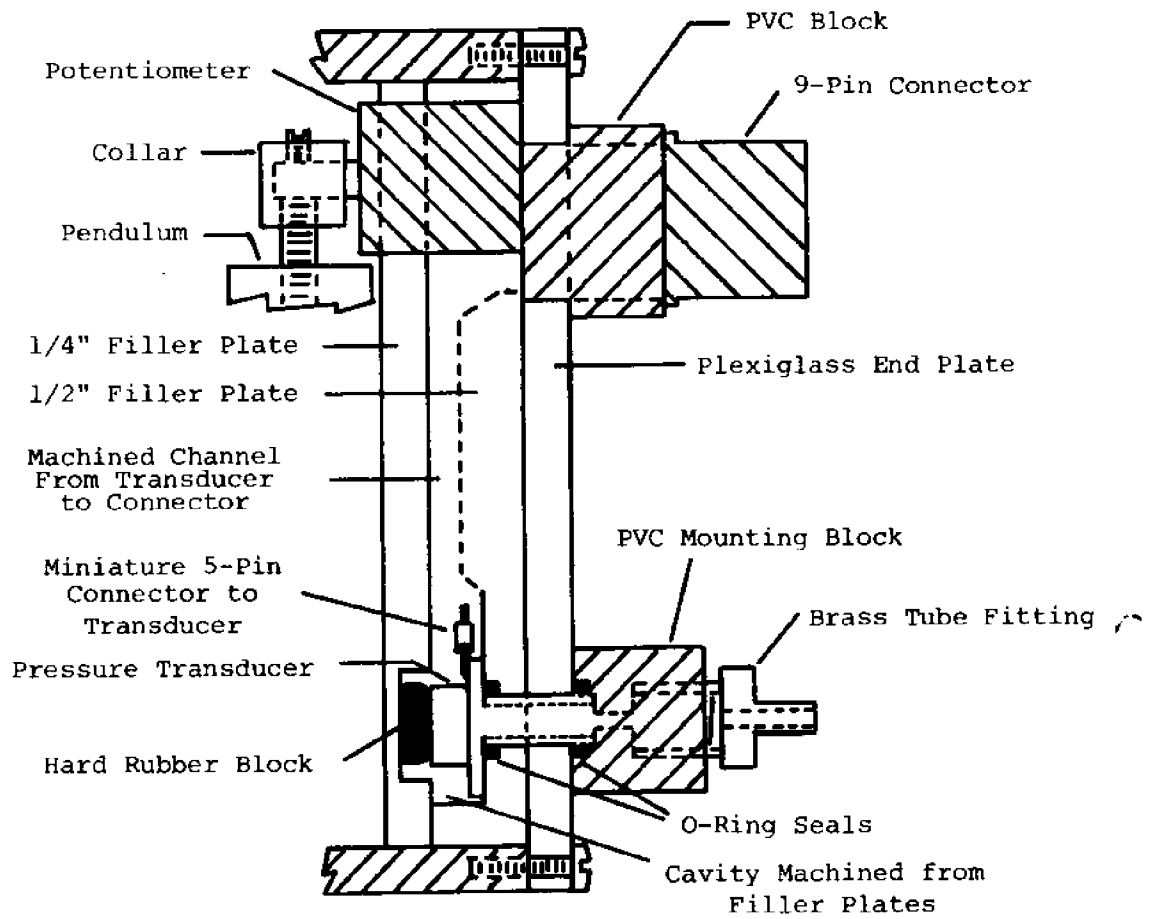


FIGURE 5.10 (cont.) Interior Detail of Pressure Transducer Mounting Technique in Multi-Sensor Package



modulated the amplitude of the signal. This signal was then passed through a synchronous demodulator circuit and amplifier which produced a d.c. voltage for input to the autopilot. The a.c. signal approach overcame electrolysis problems at the expense of more complex circuitry and greater power consumption.

During laboratory testing, the device performed well within the required accuracy limits. Unwanted fluid oscillations were self-damped due to the design of the tube. The sensor operates in the  $\pm 40$  degree roll range. Due to its small size, the sensor could be mounted directly to the circuit board containing the signal processing circuit and installed in the autopilot tube.

#### 5.2.3.2 Pendulum Operated Roll Sensor

A second roll sensor was constructed by attaching a 5 ounce lead pendulum, 2.5 inches long, to a very low torque (0.15 in.-oz.) single turn, 500 ohm potentiometer. Fluid damping of the pendulum was achieved by placing both pendulum and potentiometer in a container filled with silicone fluid.

The container was constructed from a 1.5 inch section of 4 inch inside diameter PVC tubing with 0.25 inch wall thickness and 0.25 inch plexiglass and plates secured to the tube with screws and silicone rubber adhesive/sealant. Additional plexiglass discs of 0.25 and 0.50 inch thickness were attached to one end plate for purposes of securing the potentiometer and holding other components. To aid in damping, the clearance between the pendulum and plexiglass plates was limited to 0.05 inch. This package was also used to house the pressure transducers, as shown in Figure 5.10.

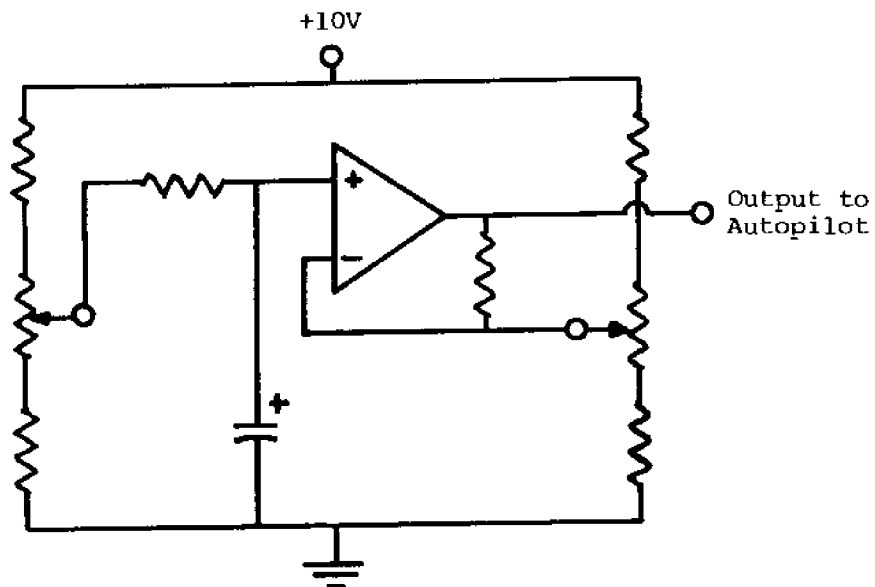


FIGURE 5.11 Pendulum-Operated Roll Sensor Circuit

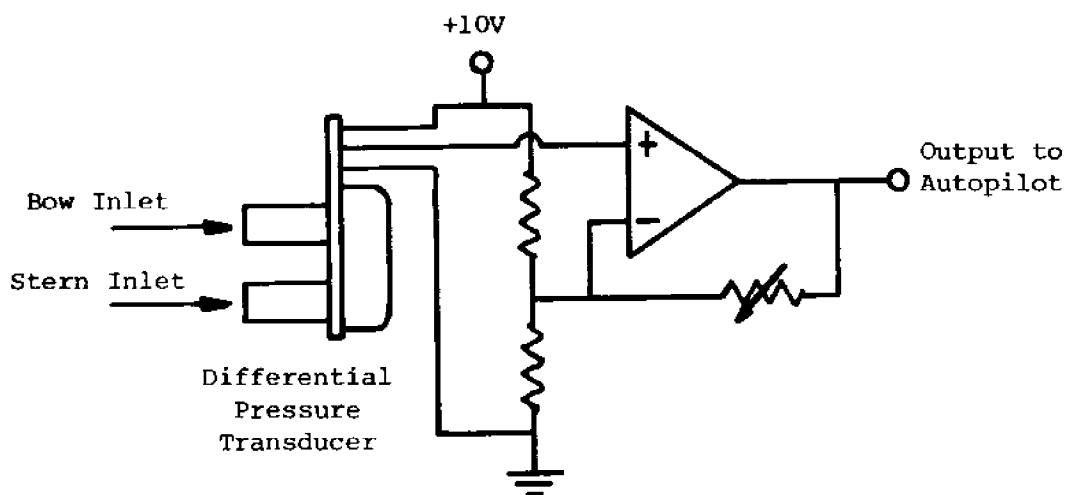


FIGURE 5.12 Differential Pressure Gauge Response Conditioning Circuit

The pendulum was formed by pouring molten lead into a machined, aluminum mould. An aluminum collar was machined to ensure that the pendulum would hang perpendicularly from the potentiometer shaft, thus maintaining the 0.05 inch pendulum to wall gap.

The potentiometer was securely mounted in the 0.5 inch filler plate. Both filler plates were then secured to the end plate with screws and adhesive. The entire container was mounted on the forward submersible bulkhead.

Under gravitational pull, the pendulum would maintain the potentiometer wiper in one position. Rolling motion of the submersible rotates the resistive element of the potentiometer. Thus roll is translated into a varying resistance which regulates a d.c. signal. This signal is then amplified and passed to the autopilot.

The signal conditioning circuitry shown in Figure 5.11 was relatively uncomplicated, with +10 V being applied across the potentiometer in a simple voltage divider arrangement. This circuit generated a 5 V output signal voltage when the submersible was level. Each one degree of roll varied this signal by  $\pm 1.8$  millivolts, negative for left roll and positive for right roll. The output was then amplified to 70 millivolts/degrees which was passed to the autopilot.

This device accurately responds to roll angles of less than one-half degree, is sufficiently self-damped to filter out unwanted pendulum oscillations and consumes approximately 100 milliwatts.

#### 5.2.3.3 Differential Pressure Transducer Pitch Sensor

It was possible to determine pitch angle by detecting the pressure difference between nose and tail as the submersible nosed up or down.

Neoprene air bladders were connected to the inlet ports of a differential pressure transducer with one-sixteenth inch inside diameter Tygon tubing. Each bladder was mounted inside a 2 inch diameter PVC tube 3 inches long with 0.5 inch thick PVC end caps. A series of three small holes, 0.5 inch apart was drilled in each tube parallel to the central axis. The tubes were mounted parallel to the central axis of the submersible with the holes facing outward, perpendicular to the fluid flow. Thus, pressure effects on the bladders due to forward motion of the submersible were minimized. The tubes were secured to the bow and stern bulkheads, 53 inches apart, at the same vertical and horizontal distance from the radial axis of the submersible. Thus one degree of pitch would create a vertical separation of 0.925 inch or a pressure differential of about 0.04 psi in seawater.

The differential pressure transducer used has a pressure range of  $\pm 5$  psig over a 9 V output span with full scale accuracy of 1.5%. As the submersible changes attitude from nose down to nose up position, the inlet ports switch roles, i.e., the nose port changes from a high pressure port to a low pressure port and vice versa for the tail port. The transducer compensates with its ability to work in the "negative" pressure region.

The output voltage conditioning circuit shown in Figure 5.12 produced a 5 V reference voltage when the submersible was level,

decreasing to 2.25 V at 40 degrees declination and increasing to 7.75 V at 40 degrees inclination. This signal was passed to the autopilot. Transducer output, when driven at 10 V, was 24 millivolts/degree pitch. The circuit amplifies this output to 69 millivolts/degree pitch.

#### 5.2.3.4 The Roll and Pitch Sensor Package

The concept of installing three sensors in one physical housing, exposed to the sea, evolved as ways were examined to better utilize space formerly wasted by the filler plates of the pendulum roll sensor. The wafer thin pressure transducers were easily mounted in a machined recess in the 0.5 inch thick filler plate, as shown in Figure 5.10. Three brass fittings were mounted in a PVC block and fastened to the end plate, in order that the Tygon tubes from the air bladders might be connected to the pressure transducers. The inlet tubes of the transducers penetrated the end plate through double O-ring seals leading into the PVC connector block. The various cavities and channels needed to accommodate these components were so constructed that silicone fluid would fill all unused spaces.

A nine pin underwater connector was installed in the same end plate as the pressure tube connector block. Thus the +10 V excitation voltage to each device and the three output signals were connected to the autopilot circuitry. One circuit board mounted in the autopilot tube contained the electrolytic roll sensor as well as the three circuits, shown in Figures 5.8, 5.11 and 5.12.

Two threaded holes were tapped in the PVC container to permit filling with the fluid. After all air was expelled, O-ring sealed aluminum screws were inserted in the holes. Even with the numerous body

penetrations, requiring both O-ring seals and silicone rubber sealant, the multi-sensor has performed adequately under pressure.

The multi-sensor was mounted on the forward bulkhead above and to the left of the autopilot housing. Holes were cut in the bulkhead enabling the underwater connector and pressure tube fittings to pass through the bulkhead, pointing forward. The depth sensor aid bladder was mounted directly to the depth transducer fitting. Tygon tubing connected to the differential inlet ports passed aft through the bulkhead to the pitch sensor air bladders.

The multi-sensor was easy to mount and remove, occupied a minimum of space which had previously been wasted, and allowed extra room in the autopilot housing for needed circuit boards.

The performance of all four sensors was equal or better than initial design criteria. However, the choice of which roll/pitch technique is best suited to this size submersible will be determined in part by further experimentation with acceleration and temperature effects on the devices. Further testing is needed with the sensors in place and the submersible under controlled motion as in the ship model towing tank.

Following are recommendations for specific sensors:

1. The pressure transducer in the depth sensor must be replaced with a transducer permitting 200 foot depth operation.
2. A thermal compensation circuit must be added to the electrolytic roll sensor.
3. A small version of the pendulum roll sensor is possible using a 0.075 in.-oz. torque mini-potentiometer and a much smaller pendulum.

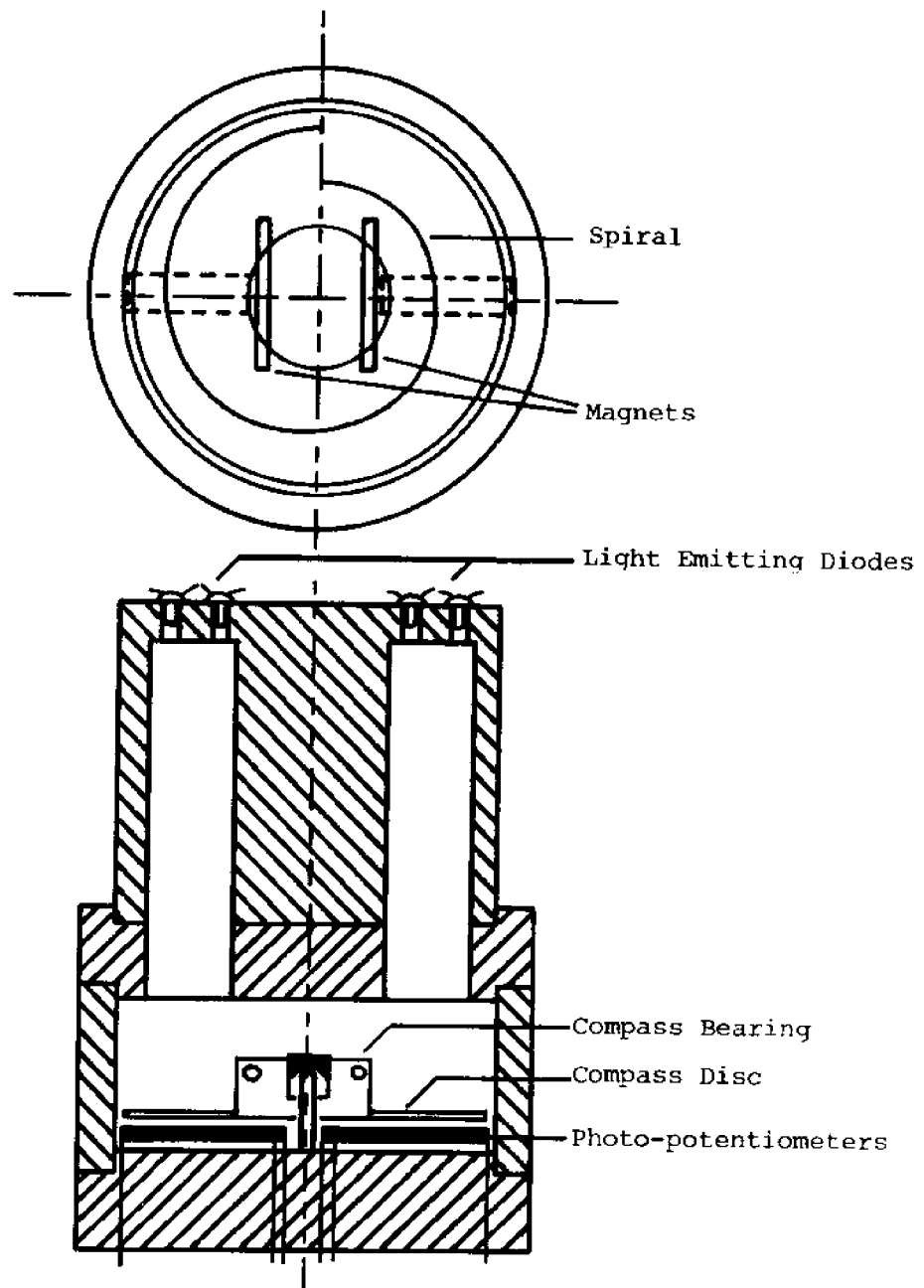


FIGURE 5.13 Arrangement of the Compass

4. If the multi-sensor package concept is retained, redesign is necessary to reduce the number of O-ring seals and penetrations.

Finally, a complete analysis of acceleration effects on each device must be made once a set of performance characteristics is available on the submersible itself.

#### 5.2.4 The Compass

A compass with an electrical analog output was required to provide heading information for the autopilot. After considering various methods of providing a voltage signal indicative of heading it was decided to use photo-potentiometers in conjunction with a compass disc. A photo-potentiometer divides the potential across the device as a function of the position of a spot of light directed on it. The compass disc has a transparent spiral on it so that with a fixed light source and photo-potentiometer the position of the spot of light arriving at the photo-potentiometer depends on the compass heading.

The principle described in the previous paragraph was proposed early in the design of the robot, but many problems prevented the rapid development of a successful instrument. The initial problems were associated with the provision of adequate bearings and the construction of a light-weight disc with an accurate spiral. The bearing was taken from an existing compass. The spiral was cut on a 1/32" thick plexiglass disc sprayed with black enamel using a "rotary table" placed on a milling machine.

Early experiments with this device showed that care had to be taken with the optical arrangement. Internal reflections in the



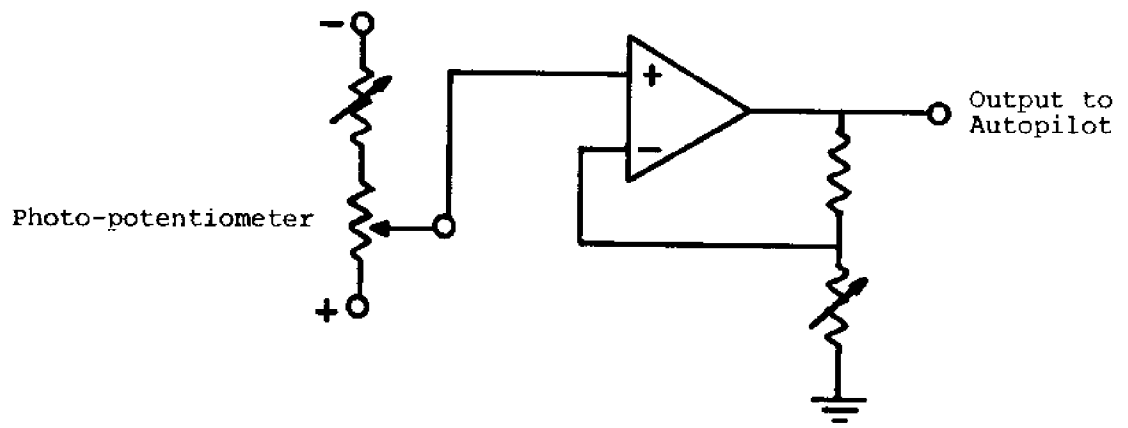


FIGURE 5.14 Compass Circuit

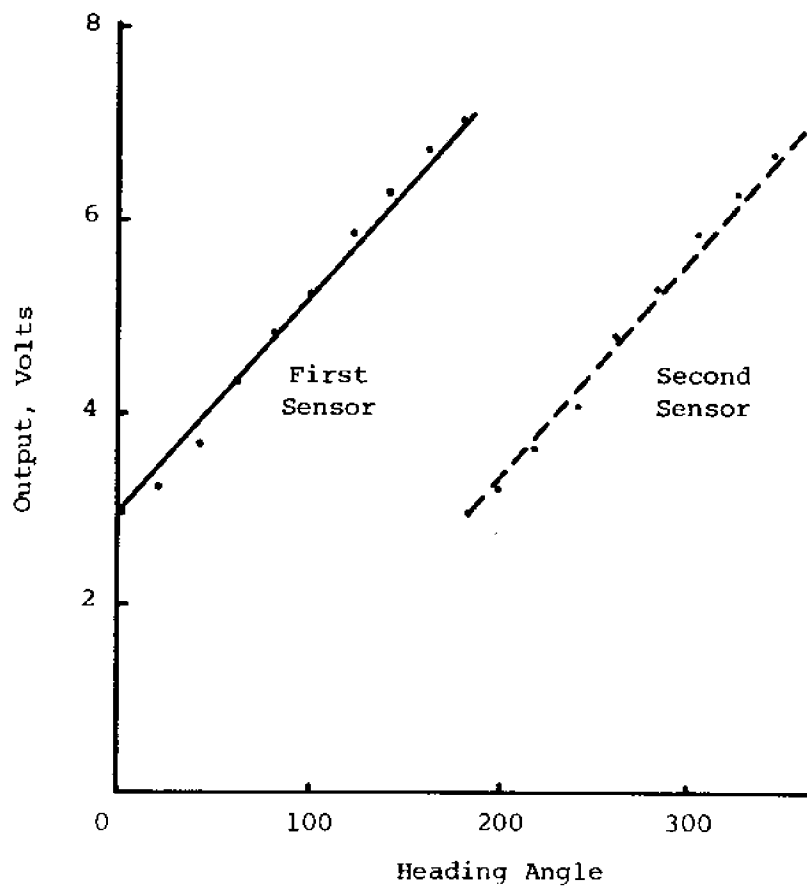


FIGURE 5.15 Compass Calibration

instrument distorted the output so that all surfaces had to be blackened. A further problem occurred when the spot of light was at the two ends of the spiral. Instead of a quick jump from one end of the spiral to the other there was a region of 8 degrees where the output was intermediate between the two end values. It was decided that two photo-potentiometers would be required and the computer would make the decision which one to use. The final arrangement of the compass is shown on Figure 5.13.

The light sources for the instrument are light emitting diodes (LED) and with these sources and the narrow spiral in the compass disc, the small illumination of the light spot results in a very high impedance output. In order to condition the output signal to the values required by the autopilot it was necessary to use an operational amplifier with a very low bias current (15 pA). The circuit used for the conditioning is shown in Figure 5.14. The output calibrations for the compass are shown on Figure 5.15.

## 6. CONCLUSIONS AND RECOMMENDATIONS FOR THE ROBOT PROJECT

### 6.1 TESTING AT CASTINE

The submarine was finally ready for ballasting the last week of the Summer Laboratory at Castine, 1974. The digital computer was not debugged yet and was replaced with 10 lbs. of lead shot, in the computer tube.

A 50 foot cable and control box were used to control the submarine. The control box controlled the motor and fin servos directly by bypassing most of the autopilot circuits and permitting the vehicle to be "flown" manually.

The Maine Maritime Academy had designed and constructed an excellent catamaran for handling the submarine. A crew of six was used to deploy and recover the submarine with two people turning the fore and aft hand winches and the remaining four at the right and left bow and stern handling tag lines and guiding the submarine in the well. This arrangement proved vital to avoid damage to the fins.

The first powered tests were conducted with the submarine in the well of the catamaran. At this point all fins were tested as well as the main propulsion system. The catamaran and submarine were then taken to open water. With the catamaran securely anchored, the submarine was guided by hand out of the well. The first tests consisted of running the submarine out to the full length of its 50 ft. control cable, then hauling it back and trying another 50 ft. run.

It is difficult to analyze the maneuverability of the submarine in these tests due to the load of the cable, which created considerable drag. During these trials, two major difficulties were encountered. First, the mechanical transmission from the fin servos to the fins were inadequate, resulting in erratic fin behavior. In spite of this, several shallow dives were tried. It was then discovered that the main propulsion control system was affected by the vehicle depth and became erratic below about four feet. The submarine was shut down and recovered with the aid of a diver to guide it into the well. That evening the control system was extensively tested and found to work properly. In the water tests were continued the next day with the same results. It was suspected that the propulsion control problem is due to an electrical leakage path somewhere in the control or connector. The control signals used were of very high impedance. Consequently, a current of 200 microamperes should be adequate to cause failure. This is easy to remedy but there was no time for further testing.

## 6.2 CONCLUSIONS AND RECOMMENDATIONS

A robot submarine has been built and although it was not operated as a robot during the Summer Laboratory it was able to operate on a tether, controlled from a switch box.

The main construction of the hull was successful with only a few minor improvements to be made. The propulsion system operated without problems, requiring only minor modifications to provide motor cooling. The servo-systems were not very successful and further work and redesign are called for. The battery was operated immersed in seawater without difficulty,

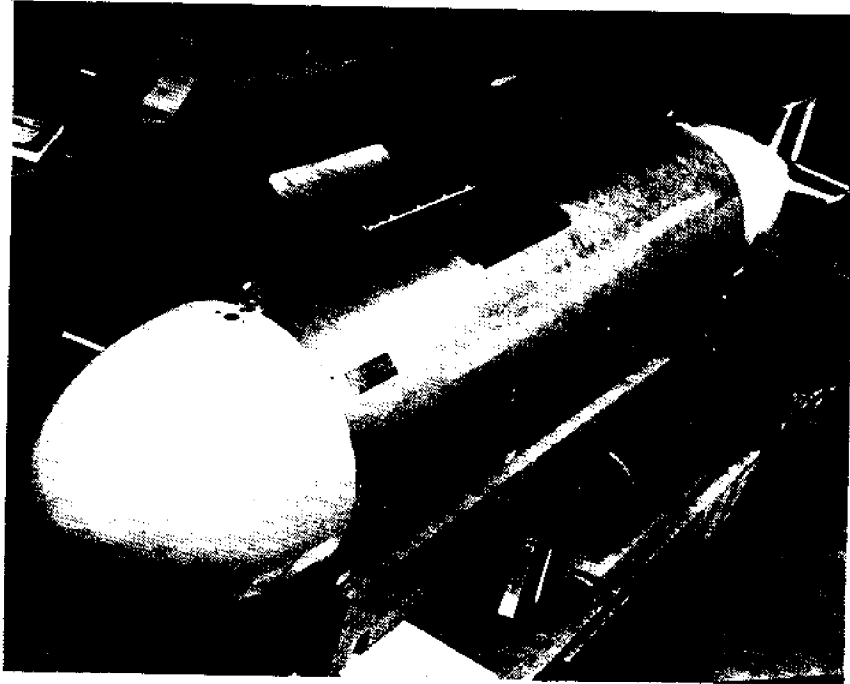


FIGURE 6.1 The Robot Submarine During Assembly

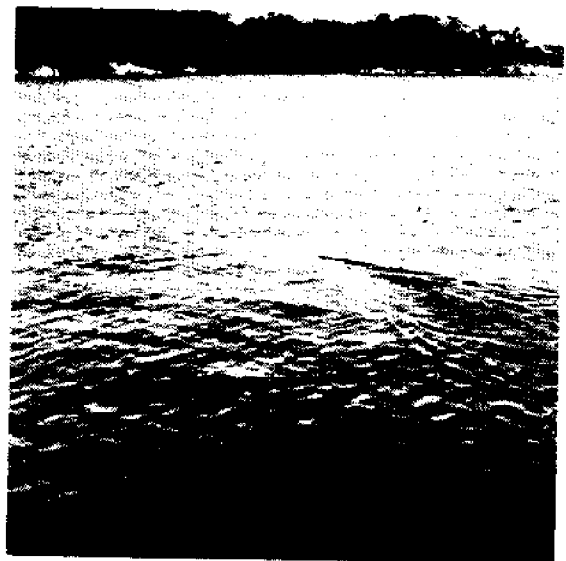
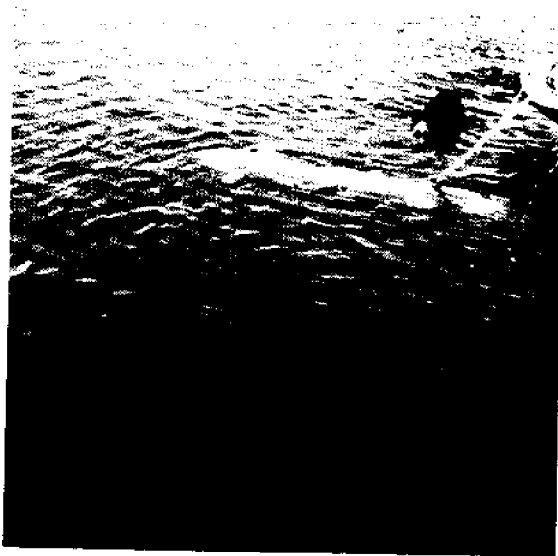


FIGURE 6.2 The Robot During Tethered Trials Near Castine, Maine

although detailed improvements to prevent loss of oil above the electrolyte are recommended. An autopilot including attitude and heading sensors has been built but not adequately tested. A mini-computer was built with the capability of controlling the robot. This system was operating at the end of the Summer Laboratory at Castine. The computer, however, requires debugging and the software has not been completely developed and tested.

Future development of the robot would include the implementation of the recommendations presented earlier together with the design and building of emergency and recovery systems. These systems would include collision avoidance methods, pinger and flashing light devices for location purposes, and emergency flotation arrangements in the event of leakage of any of the watertight tubes.

The design and construction of instrumentation for specific oceanographic or other mission will await the development of a reliable well controlled robot.

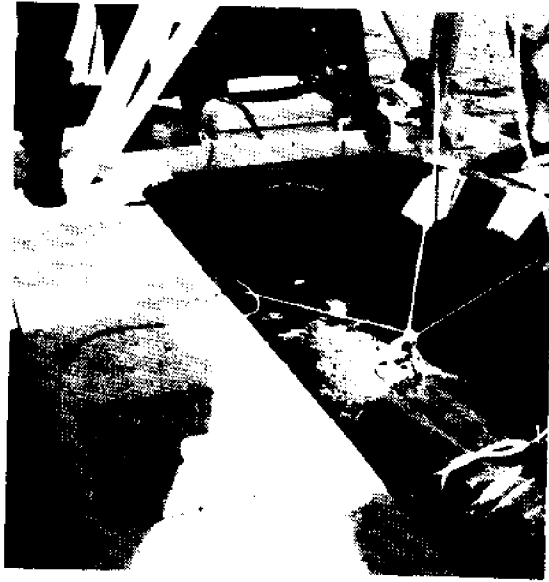


FIGURE 6.3 The Robot Submarine and the Support Catamaran

## 7. CATAMARAN SUPPORT VESSEL FOR THE SUBMERSIBLE ROBOT

With the building of the MIT submersible, "Albertross", it was decided that a suitable craft to handle the submersible was needed. The craft was to meet the following requirements:

1. Must have a lifting rig of sufficient strength to lift the robot when full of water (600 lbs.).
2. Must have sufficient buoyancy to enable the safe carrying of the robot, crew (4 persons) and whatever equipment would be needed to control the robot.
3. It had to be highly maneuverable.
4. It must be so designed as to enable the easy storage and transportation of the craft.
5. The design had to be easily and inexpensively completed in a short time.

The result of these specifications are all present in the R. V. Edsal Murphy, a 15' catamaran with an A frame lifting rig over the central well.

### 7.1 METHOD OF CONSTRUCTION

The catamaran was built in basic pieces which are jointed together by various fastenings, Figure 7.1. The components of the craft were the hulls, the decks, the transom, and the A frames.

The two pontoons measure 15' in length, 2' depth and 18" beam. The two pontoons were built simultaneously to insure identical hull form. The side panels were made of 3/8" exterior grade plywood, with chines and gunwales formed of 7/8" x 1 1/4" oak strips. The plywood was butted and strapped together; all joints glued with waterproof glue and fastened with silicon bronze boat nails.



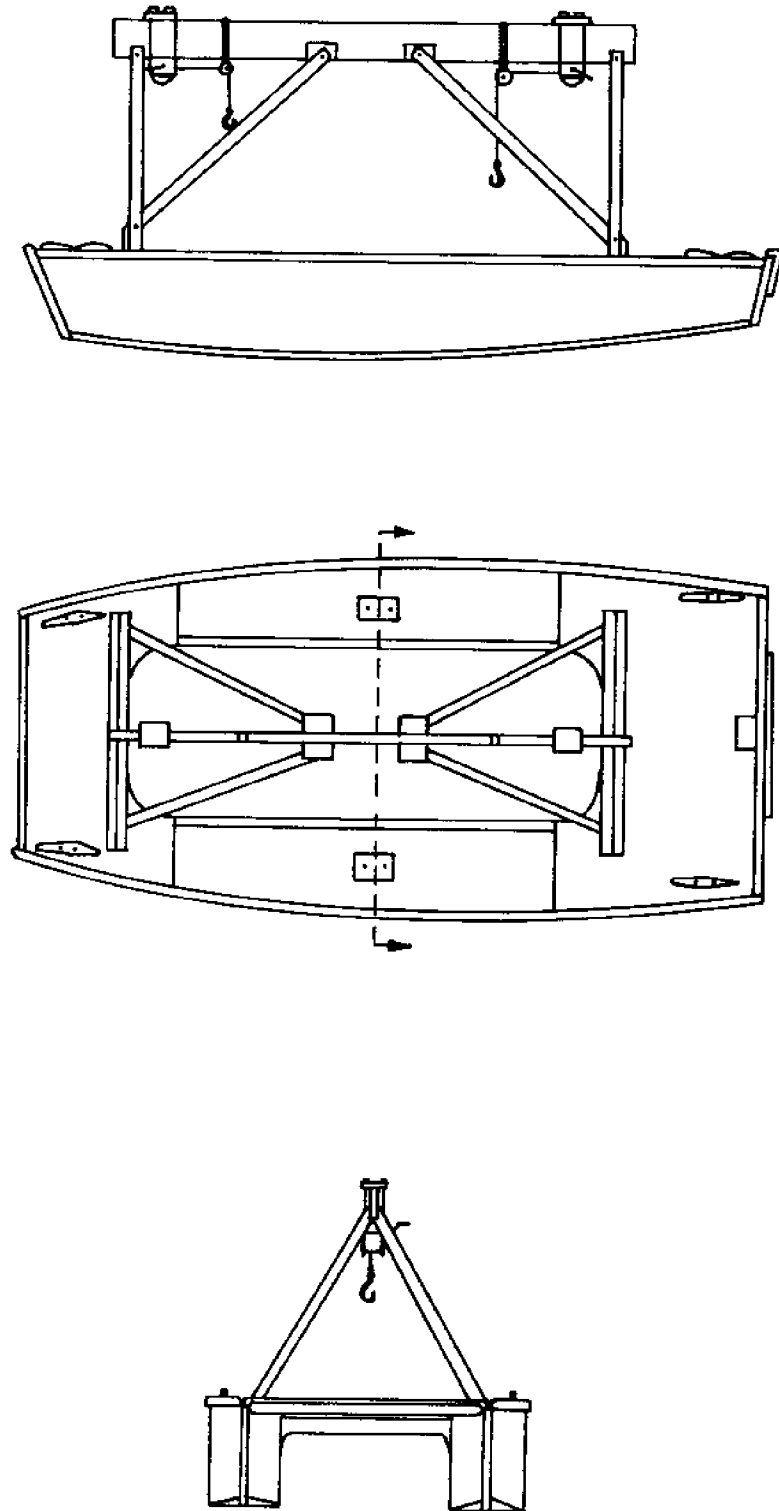


FIGURE 7.1 15 Ft. Catamaran

The completed sides were then glued and fastened, using galvanized wood screws, to the oak stems. Once jointed at the bow the sides were bent about three stations. The stations were 3/4" exterior plywood with limber and lightening holes. The sides were joined at a transom also of 3/4" plywood construction. All joints were glued and fastened as before.

Once the sides were shaped around the stations and fastened, the bottoms of 1/2 inch plywood were installed. After preparing the seams by grinding and rounding, a layer of 4" fiberglass seam tape was laid on all seams and joints.

The decks were made up in several sections, but only the middle portion of the pontoon decks were permanent. First a seven foot section was decked over with 3/8" exterior plywood. Over this was laid a second layer of 3/8" plywood. The second layer was so cut so that a well deck could be laid over the central well and butt up against the middle decks. The two layers were glued and fastened together.

The joints were caulked with latex caulking compound then fastened to the pontoons with galvanized wood screws. Each deck had a cut-out hatch to give access to the interior of the pontoons for pumping the bilges and as storage for lines and the bilge pump.

The fore and after decks were next built of similar construction, each of 3/4" exterior plywood. The decks were cut to conform to the shape of the pontoons and to allow for a ten foot long central well. The foredeck is two feet long and the after deck is three feet long, giving sufficient working and sitting space. Both decks were stiffened with spruce 2" x 4"'s.

The decks served as the main connecting members with additional strength gained with the addition of the connecting transom and the deck braces of the lifting 'A' frame.

Before caulking and fastening, the deck hardware was attached. Four cleats and the bases of the lifting 'A' frame were first doubled, then through bolted, all hardware was of galvanized iron. The decks were then caulked with latex caulking compound and finally all were fastened with galvanized wood screws.

The actual assembly for launching was conducted on the beach just prior to launching, although all pilot holes had been driven while fabricating the sections in the workshop.

The transom was then cut and the area where the motor mounts was doubled by gluing and fastening another piece of 3/4" plywood to the piece used to join the two pontoons together. All the bolt holes were then predrilled for assembly on the beach.

The 'A' frame was built of 5' lengths of spruce 2" x 4", with a 10' x 2" x 8" spanning the well longitudinally. The rig resembled a large saw horse. Two trailer type winches were purchased, each with a 1000 lb. lifting capacity. They were mounted on the under side of the beam with 1/4" threaded rods connecting the winches to 1/4" steel span plates. To the winches were attached the lifting lines of polypropylene fair-leaded through a block on a length of chain which circled the beam. Safety hooks were fitted to the lines.

Once the catamaran was in the water and assembled it was tested. The lifting rig was tested by lifting a barrel of seawater which when

fully raised from the surface of the water weighed approximately 365 lbs. There was no apparent overload on the lifting rig.

The entire vessel was painted inside and out with marine paint. The hull was given three coats of light green, the decks and lifting frame were painted white. The interior of the pontoons were also painted. This was carried out to prevent water from soaking into the dry plywood, which might cause it to delaminate. The bottoms of the pontoons were given a coat of copper bottom paint just prior to assembly and launching.

The assembly of the catamaran took place on the beach. First the bottoms were painted, then the connecting transom was fitted to the transoms of the two pontoons. Five 3/8" galvanized carriage bolts with lock washers as well as regular washers were used on each side. Next the forward and after decks were attached using galvanized wood screws.

## 7.2 TRIALS

After initial trials, which consisted of running the catamaran with various numbers of people aboard for weight, it became apparent that more rigidity was desired in the transom. This was accomplished by bolting a block of wood on the underside of the deck butting up to the transom on either side of the motor cut-out. The block was bolted through the deck and through the transom making a good solid joint between the two.

At the request of the personnel involved with the robot, four additional cleats were added to aid in the handling of the robot. A line was rigged to prevent the accidental loss of the gas tank. Finally a combination toe rail, cap rail and rub rail was added.

In performing her duties she proved to fulfill all her requirements and duties with success. She proved to be very stable, with no noticed racking of the hulls while in a seaway. Maneuvering was easy, although one had to be careful to consider that the loaded catamaran reacted slower than when light. With or without the well deck cover in place she proved to be rather wet, particularly for those on the afterdeck. This was due to spray coming up through the central well and with a full load a large volume of water came up through the motor cutout.

The catamaran has a 9.8 hp Mercury outboard motor. With a crew of two she will reach a speed of 12 kts, though she would not plane. Loaded with the submarine and crew she reached a speed of 7 or 8 knots.

Although intended to carry a crew of four plus robot and gear, it was operated with a crew of six. This was necessary for the safer handling of the robot. The catamaran was crowded but in no way suffered from this design overload.

#### 7.3 RECOMMENDATIONS

Given the opportunity to rebuild or alter the design, it would perhaps be advantageous to widen the well from 42" to 54". This would make the installation of spray rails on the inboard waterlines of the pontoons possible. It would also relieve some of the fears of damaging fragile bow planes and stern servotubes on the submarine while maneuvering it into the well.

Another useful addition would be some sort of breakwater to prevent water from backing up into the motor cut-out causing the afterdeck to flood.

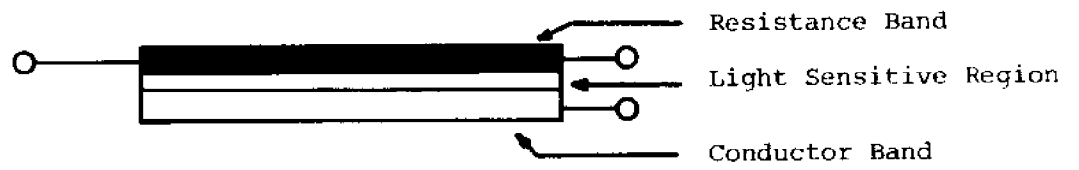


FIGURE 8.1 Light Sensitive Potentiometer

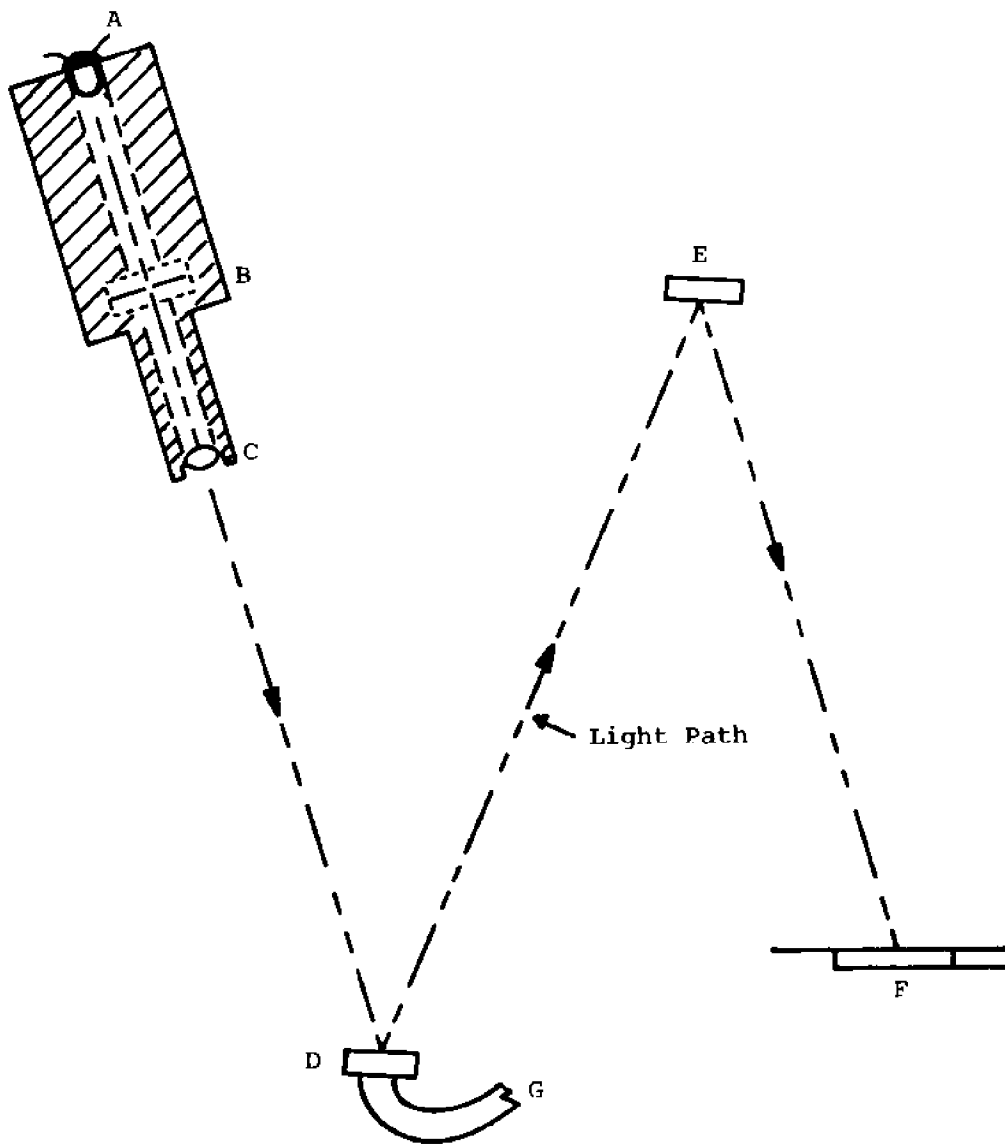


FIGURE 8.2 Optical System for Tide Gauge

## 8. A SUBMERGED RECORDING TIDE GAUGE

During the Summer Laboratory of 1973, a simple recording tide gauge was designed, built, and successfully tested in the ocean. A major limitation of this device was the fact that a fifteen foot tube had to be attached vertically to something fixed to the ocean floor such as the supports of a dock. It was decided that a major improvement would be attained if a tide gauge were designed in such a way that it could just be dropped into the water from a boat and left there for a certain period of time with no maintenance. Everything would be self contained, that is, the tide gauge, the power system, and the recording system. Moreover, the total weight of these systems would be minimized for ease of handling. Finally, the tidal readings should be continuous, not discrete, as in the previous instrument, for maximum sensitivity of the instrument.

### 8.1 DESIGN AND CONSTRUCTION

The new tide gauge is based on a new device on the market, a light sensitive potentiometer, Figure 8.1. The region along the top is the resistance band; the region along the bottom is the conductor band. Along the middle of the potentiometer is a thin band; this is the light sensitive region. The potentiometer is operated by shining a thin beam of light onto this area. Thus, the voltage across the potentiometer is determined by the position of this beam of light on the device.

As the first step in the construction of the tide gauge, a pressure gauge was taken apart and the Borden tube (see G in Figure 8.2)

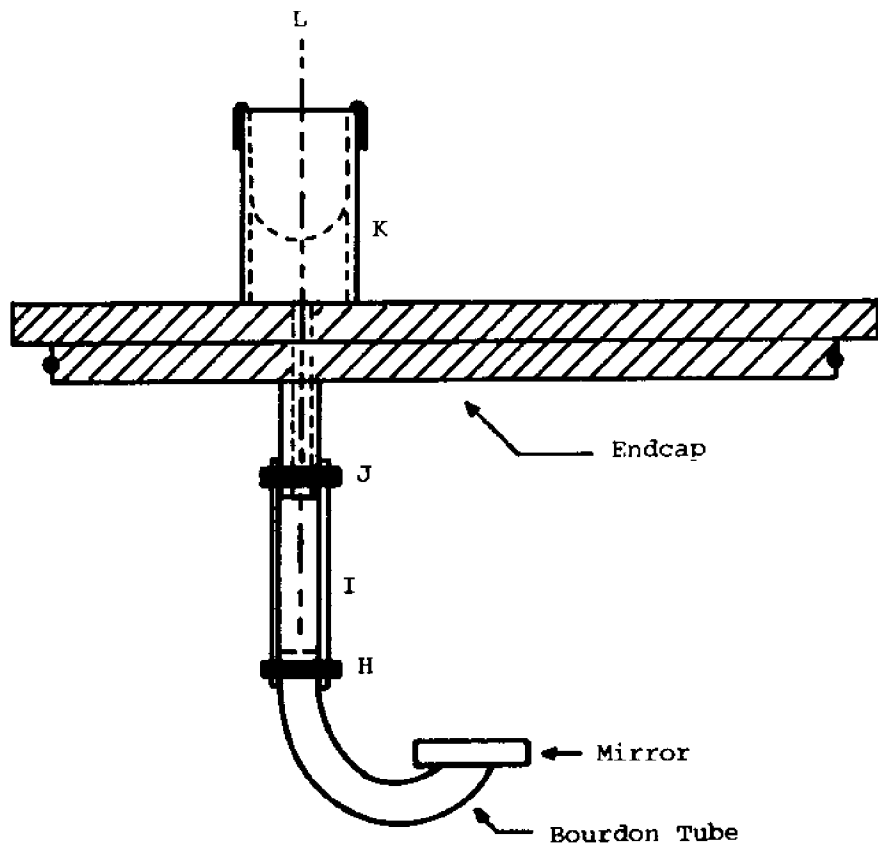


FIGURE 8.3 External Pressure Connection

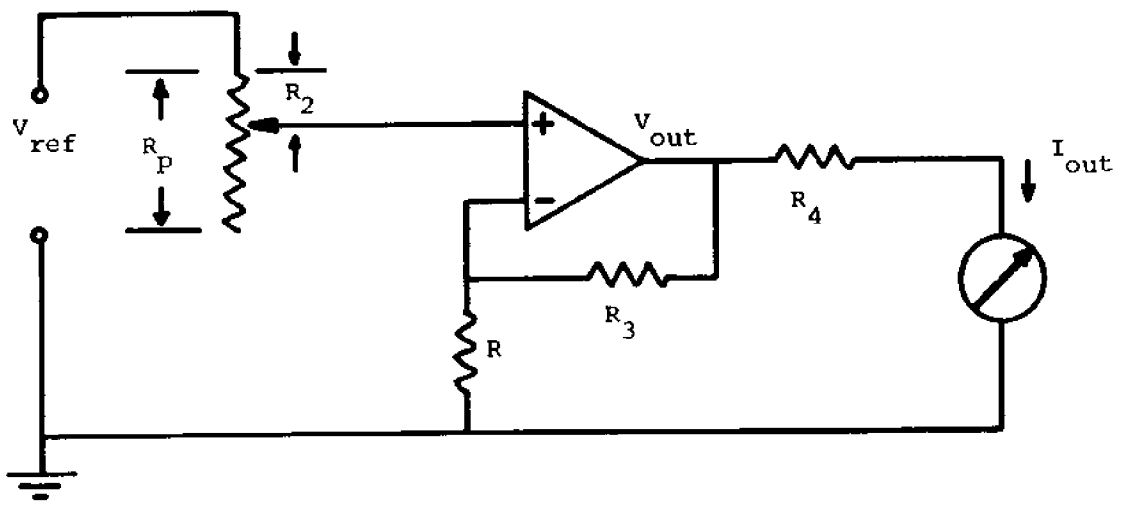


FIGURE 8.4 Circuit Diagram



was extracted. This is a curved hollow metal tube which tends to straighten itself out when the pressure inside it is increased. At the tip of this tube, a mirror was attached (D) so that the mirror rotates as the pressure inside the tube is changed.

An optical system inside a PVC block was then set up to produce a thin beam of light. This consisted of a light emitting diode (A) as the light source, a slit (B), and a lens (C) which focused the slit of light. The beam of light was directed at the mirror on the Borden tube (D), and it was reflected onto another mirror (E) to save space. From this mirror, it was then reflected onto the light sensitive potentiometer. The distance between the Borden tube mirror (D) and the potentiometer (F) was critical. It is this distance which determines what size pressure change will produce a full scale reading from the potentiometer.

This entire system, along with some electronic circuitry was enclosed within a plexiglass case to keep everything together and to protect the delicate optical balance of the instruments inside. The case was built so that it would fit inside a six inch diameter PVC tube, which had a water-tight endcap with O-ring seals on each end. It would thus remain in the water for long periods of time without leaking or corroding.

A pressure connection was made from the Borden tube to the outside environment through one of the endcaps (see Figure 8.3). A rubber hose (I) was attached by means of hose clamps to the Borden tube (H) and to a fitting on the inside of the endcap (J). Through this fitting and through the endcap, a small hole was drilled. On the outside of

the endcap, a short piece of three-quarter inch diameter PVC pipe was securely glued to the endcap (K). After all these connections were firmly made, the system (including the inside of the Borden tube) was filled with mineral oil to minimize corrosion from the seawater. When the system was full, a rubber cover was inserted into the three-quarter inch tube, thereby overflowing the oil and removing all of the air inside. The rubber cover was tied to the outside of the tube to provide a watertight seal. Thus, an external pressure connection had been made with no direct exposure to the salt water environment.

As the water pressure increases, the rubber cover flexes, thereby compressing the oil and causing the pressure inside the Borden tube to respond. This then causes the mirror on the Borden tube to change its angle relative to the beam of light. The end result of this is that the position of the beam of light on the light sensitive potentiometer is changed for any change of pressure. Pressure is directly proportional to the height of the water above the device provided the seawater density does not change.

The electronic circuitry used to produce the desired results was fairly simple (see Figure 8.4). The reference voltage,  $V_{REF}$ , was a small 1.35 volt mercury battery. It could be turned on and off by means of a switch on the outside. The circuit was designed so that the output voltage of the operational amplifier,  $V_{OUT}$ , was independent of the magnitude of the resistance of the light sensitive region across the potentiometer where the beam of light was shining on it. In other words, the output voltage

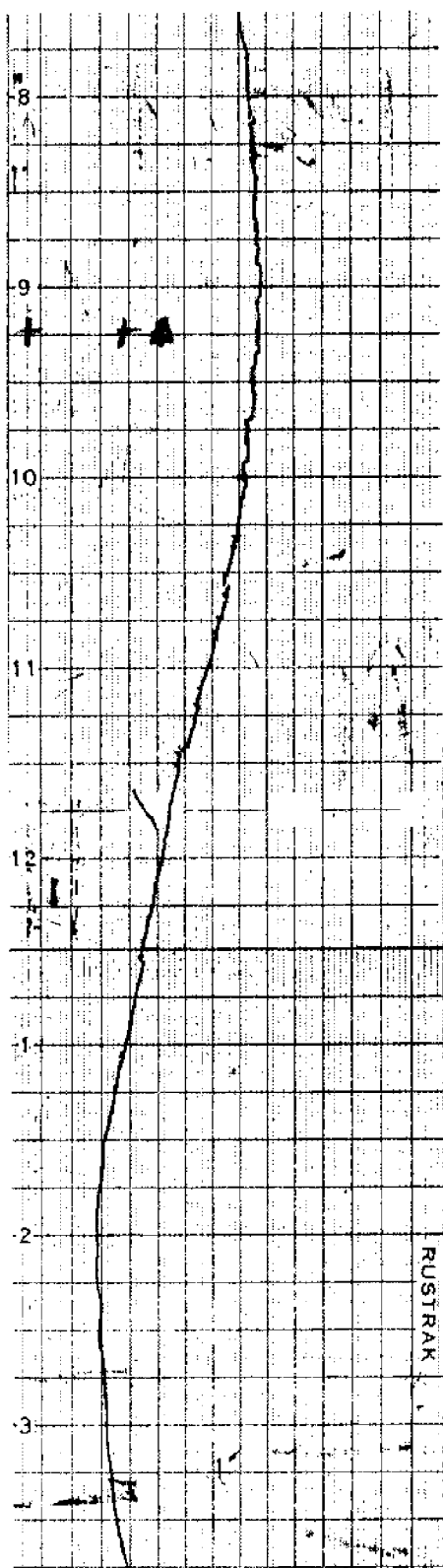
does not depend on the intensity of the beam of light shining on the potentiometer. As the pressure changed,  $R_2$  would also change, producing the desired linear result.

The gauge measures the tidal height not as a function of absolute pressure, but of relative pressure, the difference in pressure inside the PVC tube and outside it. Thus, given a constant external pressure, and a fixed volume, even a small temperature change would produce an error reading on the recording meter. To compensate for this, a thermistor was put in series with resistance  $R$ . The value of  $R$  was selected so that meter output was corrected to account for the pressure change produced by small variations in temperature.

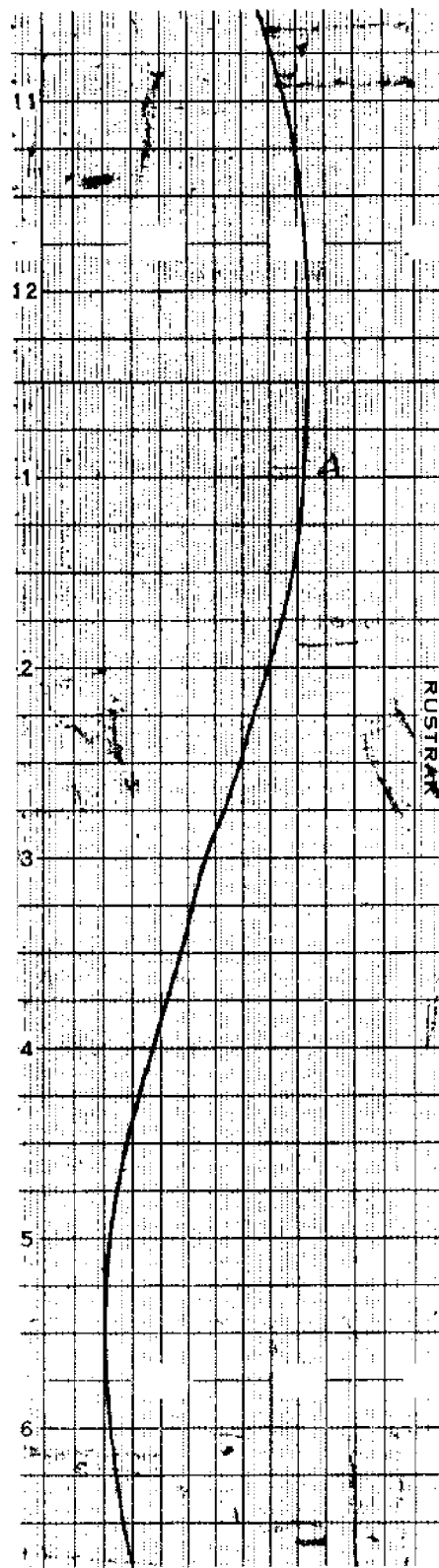
The recorder previously mentioned was a small, continuous recording device with a very low power consumption (19 ma). With a battery as the power source and a somewhat erratic motor controlling the speed of the chart paper, some kind of accurate time scale was needed. A precision watch was obtained which has two terminals on it. Every twenty minutes, the watch short circuits these terminals for thirty seconds. These two terminals were then connected to the two leads of the recorder. Thus, every twenty minutes, a reading of zero was recorded on the chart paper (see Figure 8.5b), thereby producing an accurate time scale.

## 8.2 TEST RESULTS AND INSTRUMENT DEVELOPMENT

Experiments in the laboratory revealed that the light sensitive potentiometer remained sensitive to light for several hours after it had been put into the dark. Thus, in order to be able to change the batteries



a. Before Modification



b. After Modification

FIGURE 8.5 The Tide Gauge Records

and remove the chart paper of the recorder, a dark circle of plexiglass was attached in between the tide gauge and the batteries and recorder. This permitted free access to the batteries and recorder without affecting the potentiometer.

Initial testing in the ocean, after an optimum depth of operation was found, proved very encouraging. Figure 8.5a shows an example of these results. In many places, especially around high tide, the recording deviated from a smooth sine curve. It was decided to see if a water current was the cause of this. Thus a cap, sealed at the end, with tiny holes drilled into the side, was fitted over the external pressure connection. Figure 8.5b reveals the kind of results that were obtained after this modification. It obviously was the current that was causing the disturbances.

To see if the temperature compensator was functioning properly, the tide gauge was removed from the water and allowed to heat up to air temperature (64<sup>0</sup> F). It was then quickly placed at different water levels; the readings at these levels were all automatically recorded. Later, after the inside of the tide gauge had cooled down to water temperature (middle fifties), the same procedure was repeated. A comparison of the two readings revealed that the results were nearly identical. During the time between the readings, the tide gauge was kept at a constant depth; the output was nearly constant. These two tests seem to indicate that the temperature compensator was functioning properly.

A vital part of the testing was the calibration of the instrument, that is, converting the chart readings to feet of water. By

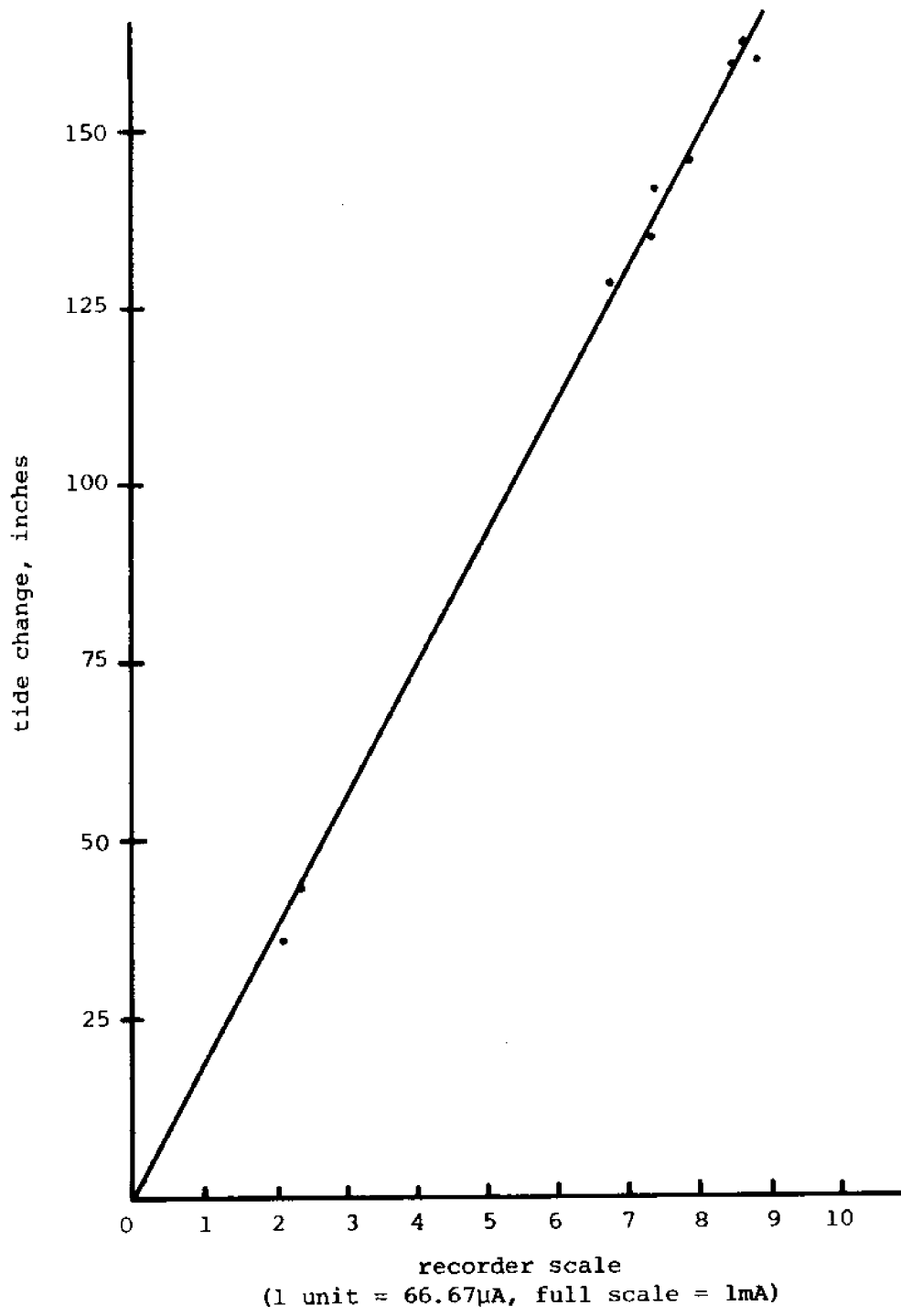


FIGURE 8.6 Calibration of Tide Gauge

comparing observed tidal height readings with those recorded by the tide gauge, making use of the time scale already described, a graph was drawn (see Figure 8.6). The scale is thus 18.6 inches water per subdivision of the chart paper.

### 8.3 CONCLUSIONS AND RECOMMENDATIONS

The greatest difficulty in the construction of the tide gauge involved the alignment of the optical system. If it was desired to place the instrument in deeper or shallower water, then the mirror at E in Figure 8.2 had to be rotated. This was a trial and error procedure. A big improvement would be to attach this mirror to some kind of gear mechanism which would rotate the mirror and could be operated by means of a dial outside the PVC tube. This dial could be calibrated to certain water depths so that the user could use the instrument in any shallow water depth he wished (up to 60 feet). A different Borden tube would have to be used for larger water depths.

Except for this modification, and perhaps the miniaturization of the optical system, no other design changes are needed. Because this device used no complicated notions, because it stood up to the perils of the sea, and because the only expensive part of it was the chart recorder, it met its goal of being simple, rugged, and economical.

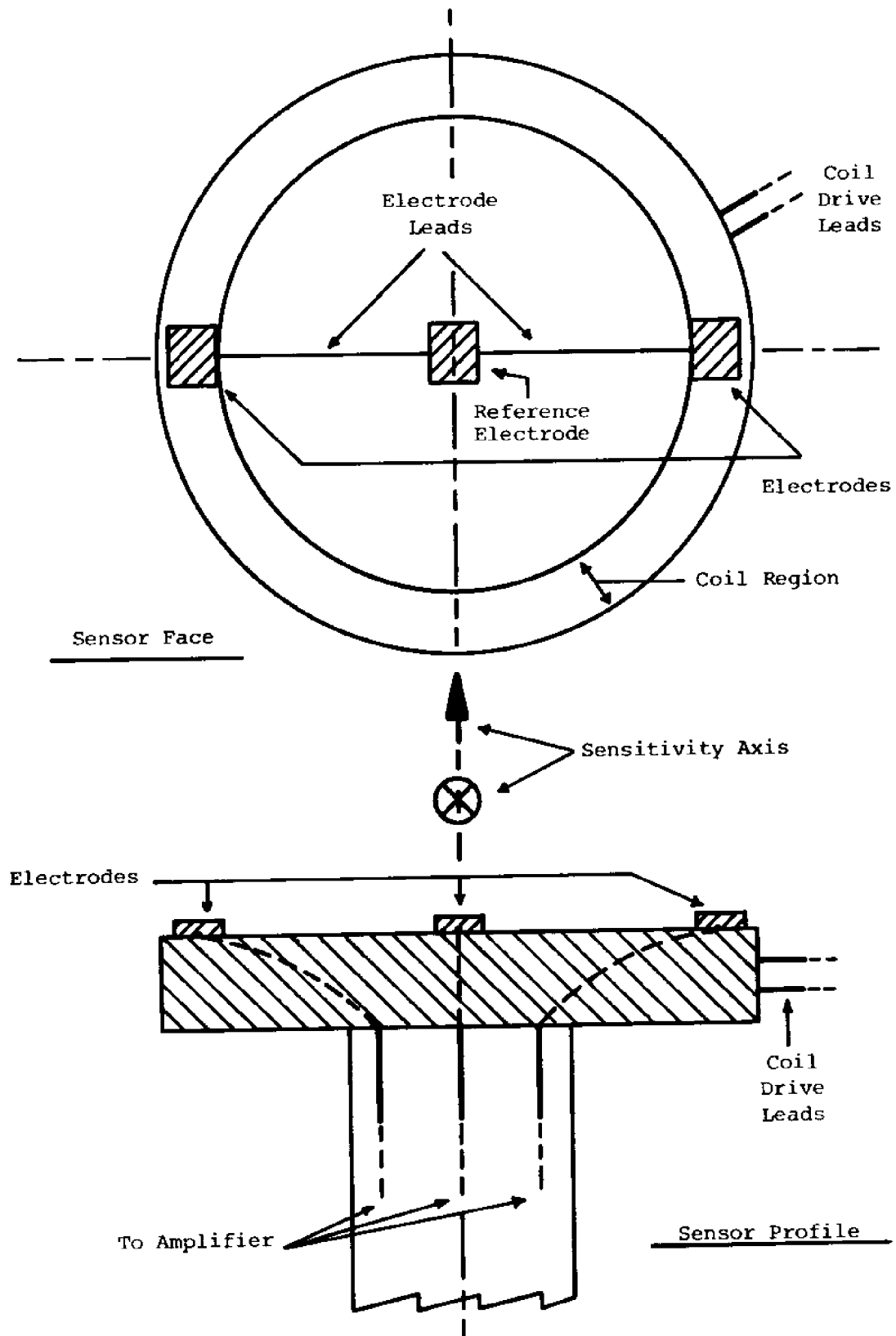


FIGURE 9.1 The Electromagnetic Current Meter Sensor Arrangement



## 9. THE DEVELOPMENT OF AN ELECTROMAGNETIC FLOWMETER

Oceanographers have long been aware of the need of a water current velocity meter that is dependable and accurate. A device using electromagnetic principles, would provide a means of producing an accurate, linear representation of water flow with the use of no moving parts.

### 9.1 THE DESIGN OF THE SYSTEM

The Lorentz Law dictates that an electric field will be produced in a direction perpendicular to both an applied magnetic field and a velocity of charged particles. A sensor which generates a magnetic field will create a voltage across electrodes housed in the sensor; this voltage is a linear function of the water velocity passing by it.

Previous experiments indicated that only an alternating magnetic field device would eliminate the effects of polarization at the electrodes. The method used here is based on ref. 9.1. The time constant of the sensor coil dictated a maximum operating frequency of twenty nine Hertz and ten Hertz were used. A square wave driving signal provides for a simple demodulating circuit.

To avoid self inductive effects, dimensional considerations indicate safety at a coil diameter of ten centimeters. A twelve hundred turn coil was wound on a PVC bobbin and potted with highly viscous epoxy resin. The coil must be well insulated from the electrodes so that the driving voltage does not divide across them.

It is important that the sensor electrodes can sustain electrochemical effects. Silver-Silver Chloride mesh was therefore used. The electrodes were mounted on the face of the coil bobbin for maximum

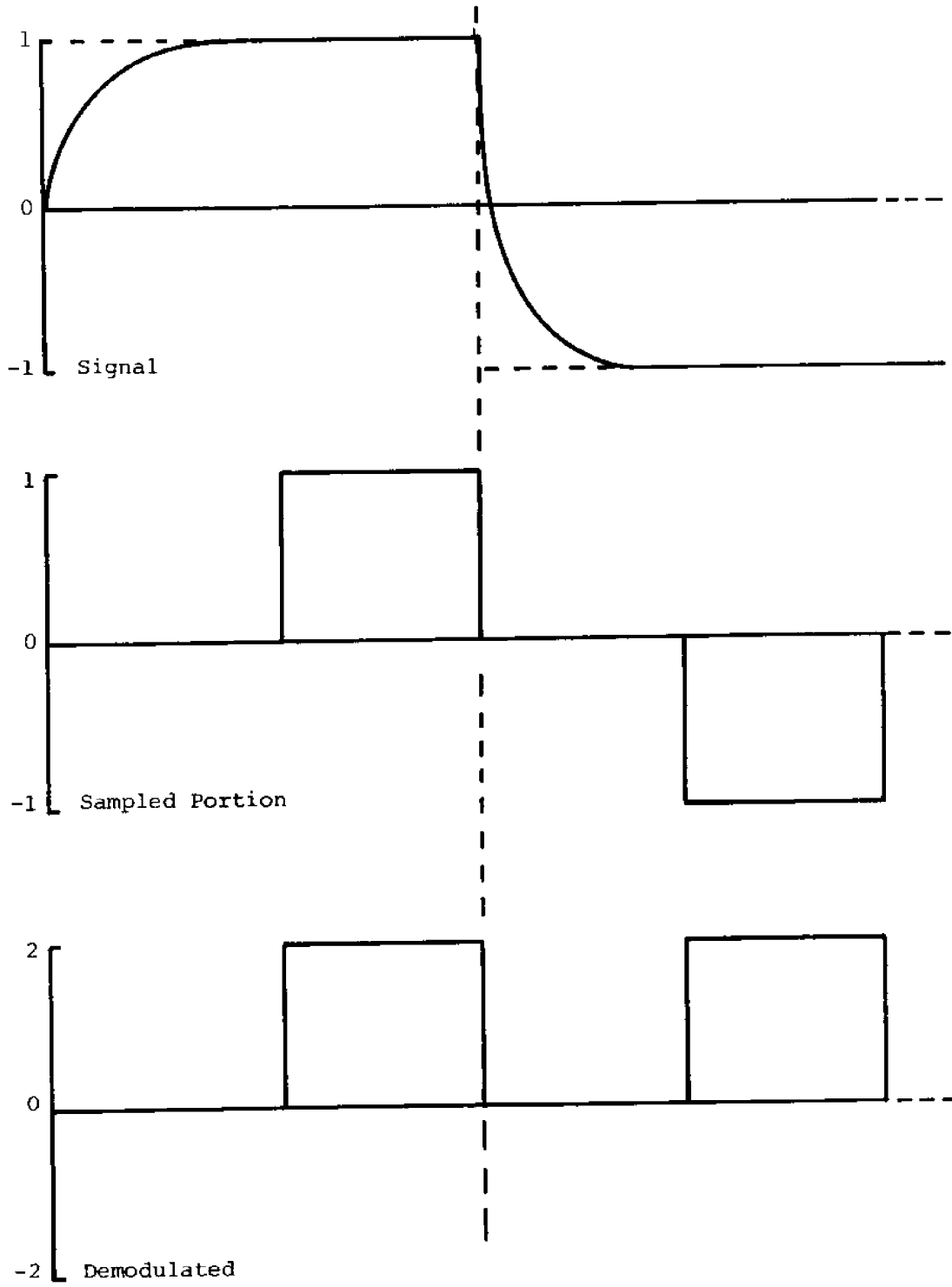


FIGURE 9.2 The Signal Processing

magnetic effect. Vectorboard with two one millimeter holes were epoxied over the electrodes as a protective covering. The electrode leads were led up through the center of the coil to reduce inductive pickup as much as possible.

The input impedance of the amplifying system must be high to eliminate the effects of variations of the resistance between electrodes. Since tap water may have an impedance of up to one hundred kilohms, the amplifying stage had an input impedance of two hundred and fifty megohms. (This is not critical for purely oceanographic use).

The signal was amplified differentially to help eliminate high frequency pickup and dc offset. Any remaining dc offset was then eliminated by a dc filter. The amplification stage was completed by multiplying the signal another one hundred times, giving a total gain of twenty thousand. The input signal was expected to be the order of microvolts.

To insure elimination of transient effects the amplified signal was sampled during the second half of each half period, Figure 9.2. The signal was then within one tenth of a percent of its final value. The demodulating system eliminated any remaining signal that was not synchronized with the driving signal. This was accomplished by multiplying the signal by two during the first part of the sampled signal and by negative two during the second part. Any stray signal constant over the demodulating period was then averaged out to zero.

The dc value of the signal was then taken, amplified and fed into a current meter for visual display, Figure 9.3.

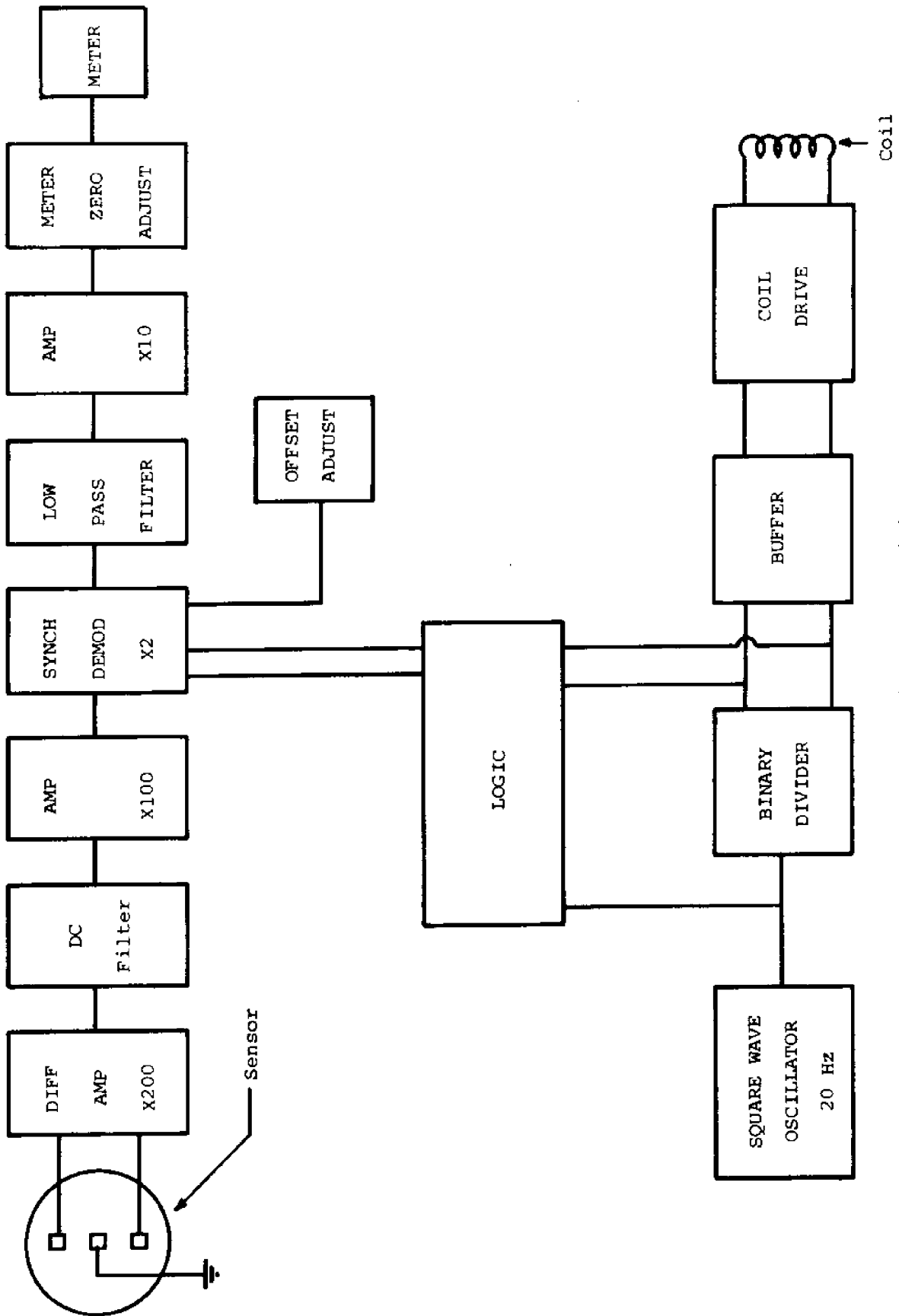


FIGURE 9.3 The Amplifying and Driving Systems

## 9.2 EXPERIMENTAL RESULTS

The circuitry was tested in the laboratory. It proved linear and reproducible with controlled inputs. It was sensitive to one eighth of a microvolt. The total current drain of the system including the coil was one hundred milliamps.

To apply this device for oceanographic use, the sensor was attached to the endcap of a waterproof PVC tube, which contained the entire amplification stage and two six volt lantern batteries. This stage drew twenty four milliamps from the batteries and could therefore remain in the water for a long period of time.

The driving circuit for the coil as well as the demodulating circuit and readout were to be used at the surface for preliminary tests.

When placed in the water on its sensitive axis the readout was stable and sizeable (positive fifteen hundredths of a milliamp). The sensor was reversed and the readout was the same in magnitude but opposite in sign as expected. When the sensitive axis was placed perpendicular to the flow direction, the readout was zero; indicating no flow as predicted.

Unfortunately, after approximately an hour of use (after being out of the water for twelve hours), the system experienced an inexplicable syndrome, which caused random fluctuations and undecipherable results.

It seems obvious that this method of producing a dependable, linear and accurate flowmeter has great potential. However, the cause of its spurious behavior after the initial functioning period must be determined and eliminated.

9.3 REFERENCES

- 9.1 Lawson, K. and Kanwisher, J., Electromagnetic Flow Sensors, Woods Hole Oceanographic Institution, March 1974, Unpublished Manuscript.

## 10. CABLE STRUMMING EXPERIMENTS

The self excited vibration of cables induced by ocean currents is of important concern to the oceanographic community. The energetic movement of the cables can induce errors in the readings of instruments supported by the cables and it is possible that the "fish bite" damage found on many cables in the ocean may be aggravated by the strumming phenomenon.

The cause of the strumming has been established as the regular shedding of vortices from the cable. These vortices form the "Karman vortex street" which occurs downstream of cylindrical bodies at low Reynolds number. The shedding of a vortex induces a transverse force which moves the cable; the subsequent shedding of a further vortex of opposite sign produces an opposing force and opposite cable movement which has the effect of sustaining the strumming action. The movement of the cable in the strumming phenomenon apparently synchronizes the vortex shedding between nodes in the vibrating cable.

The causes of the phenomenon are apparently well understood although the amplitudes of the cable vibration when strumming occurs have not been established in the ocean environment. The measurement of the amplitudes of vibrating of strumming cables in representative ocean current situations is the objective of the work described in this report. In addition, methods of reducing or eliminating strumming were also to be examined experimentally.

### 10.1 THE EXPERIMENTAL ARRANGEMENT

The ideal experimental situation would have the cable placed in the region where the current velocity was uniform over the length of the

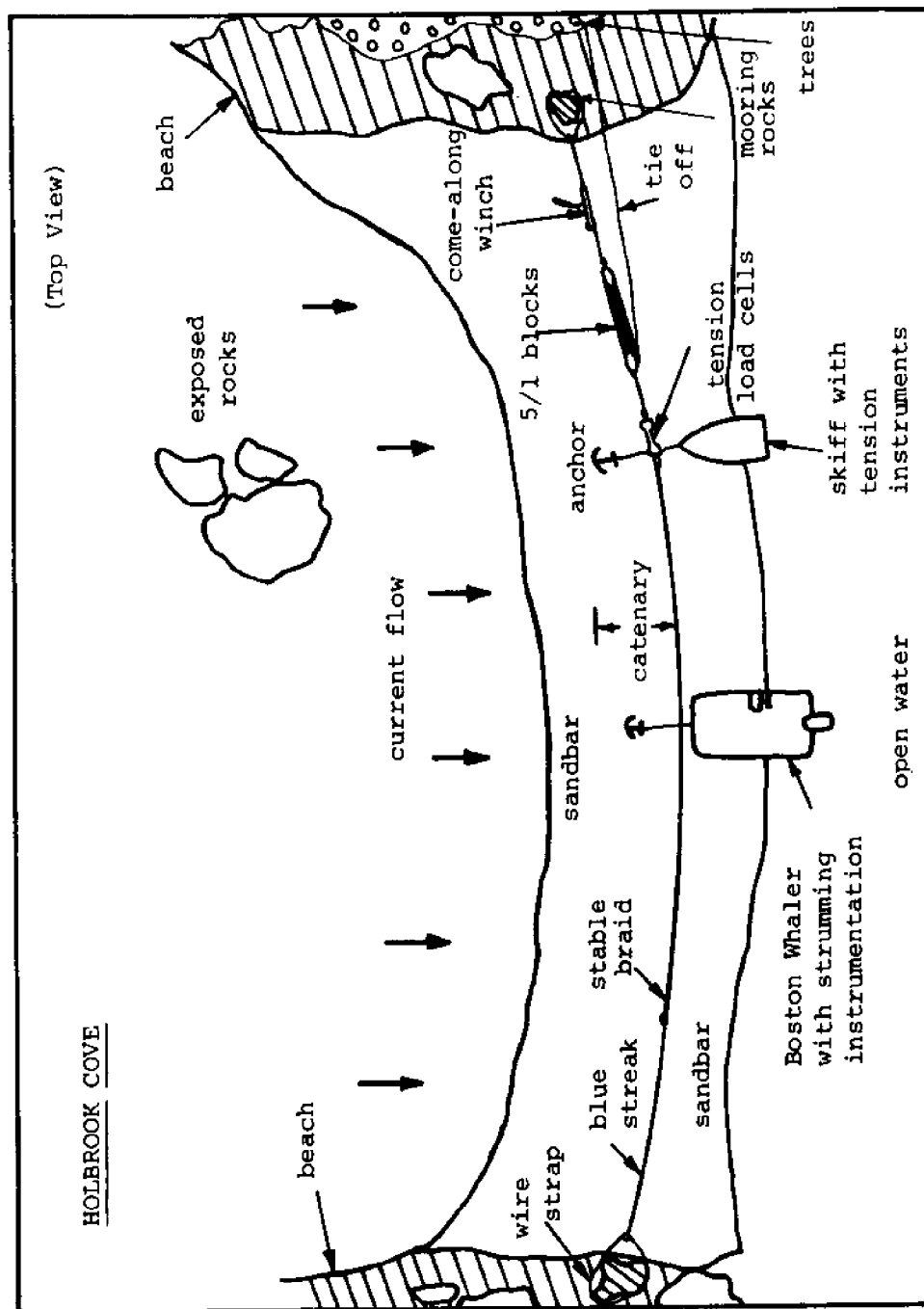


FIGURE 10.1 The Test Arrangement for the Cable Strumming Experiment



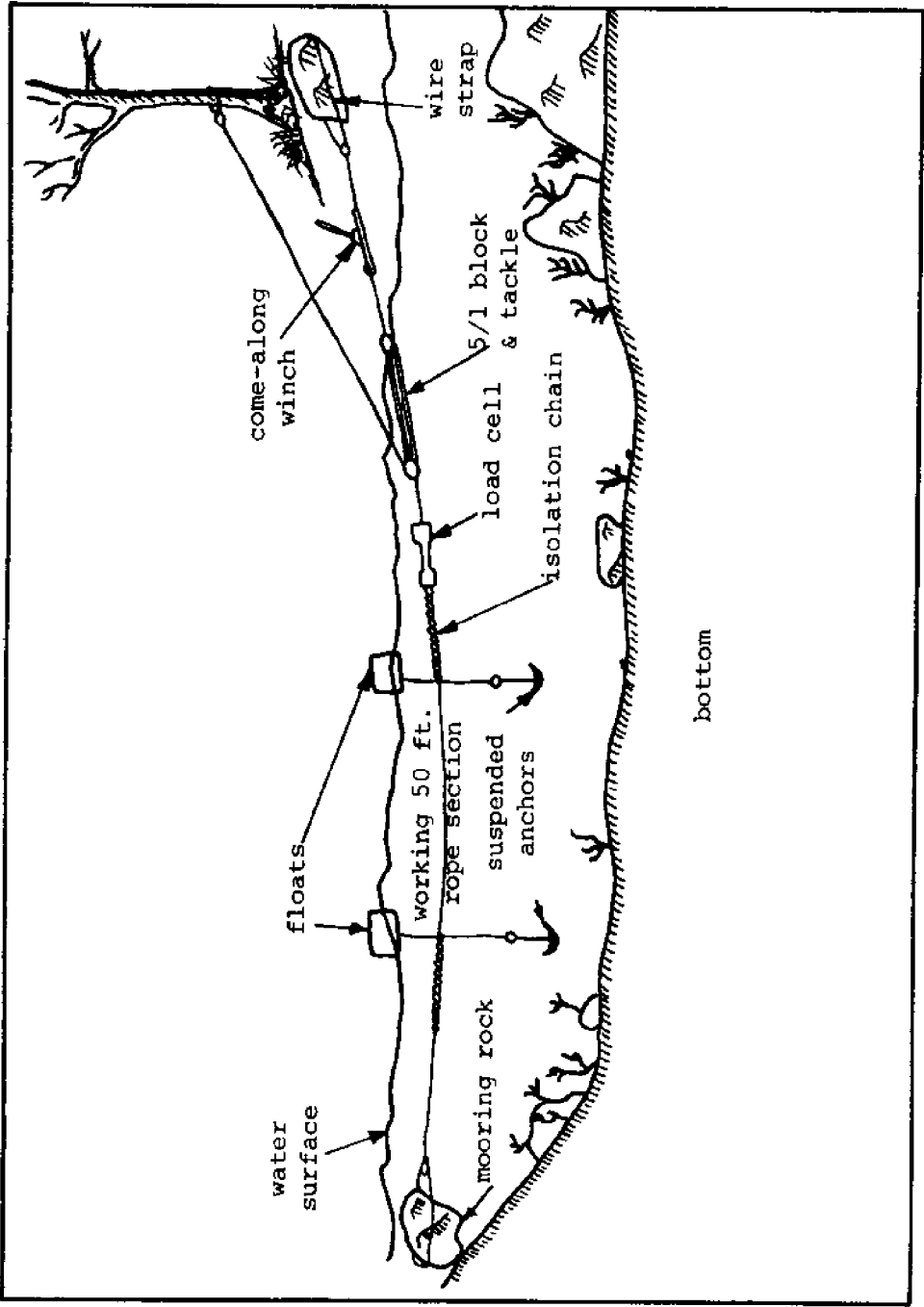


FIGURE 10.2 The Test Arrangement for the Short Cables

cable at any time but where the current velocity varied slowly as a function of time over a wide velocity range. These ideal conditions were difficult to realize although the slow velocity variation with time could be obtained in tidal waters.

A sandbar near Castine, Maine, was selected as the experimental test site. The cables were set up at low tide when the sandbar was exposed and the experiments were conducted on the rising and falling tide. The range of water velocity at this site was from zero to 0.8 knots and the velocity appeared to be reasonably uniform across the sandbar because of the venturi-like shape of the region leading to and from the sandbar. Experiments to measure the variations of current velocity across the sandbar were not conducted because only one satisfactory current meter was available at the time of the study.

#### 10.1.1 The Cable Arrangement

The cable was fixed to a large rock at one end of the sandbar and tightened and controlled at the other end of the sandbar by means of a 5 to 1 block and tackle to provide the initial tensioning, as shown in Figure 10.1. The final tension was obtained by a "come-along" winch with a twelve foot travel.

The total length of the cable was about 250 yards and a test section was arranged in the middle of the cable to test several types of ropes. A 400 ft. test section was first used but in later tests the rope samples were 50 ft. in length. The short test sections were partially isolated from the rest of the cable by using 5 ft. lengths of 3/8" chain at each end of the test length, as shown in Figure 10.2. Floats were attached

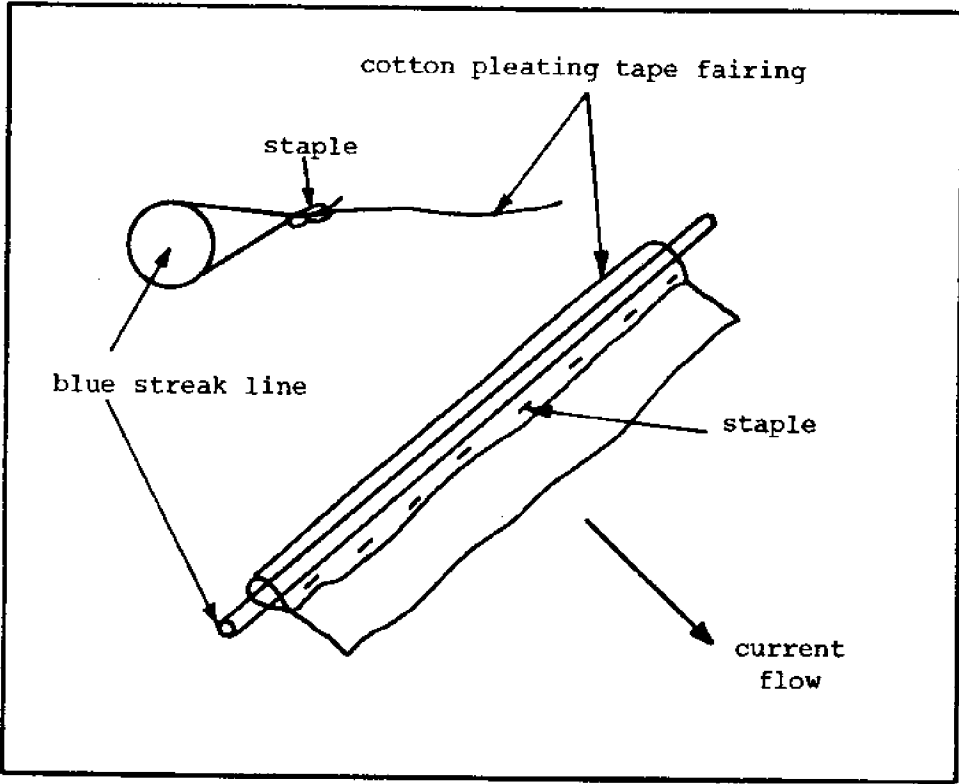


FIGURE 10.3 A Simple Anti-Strumming Fairing

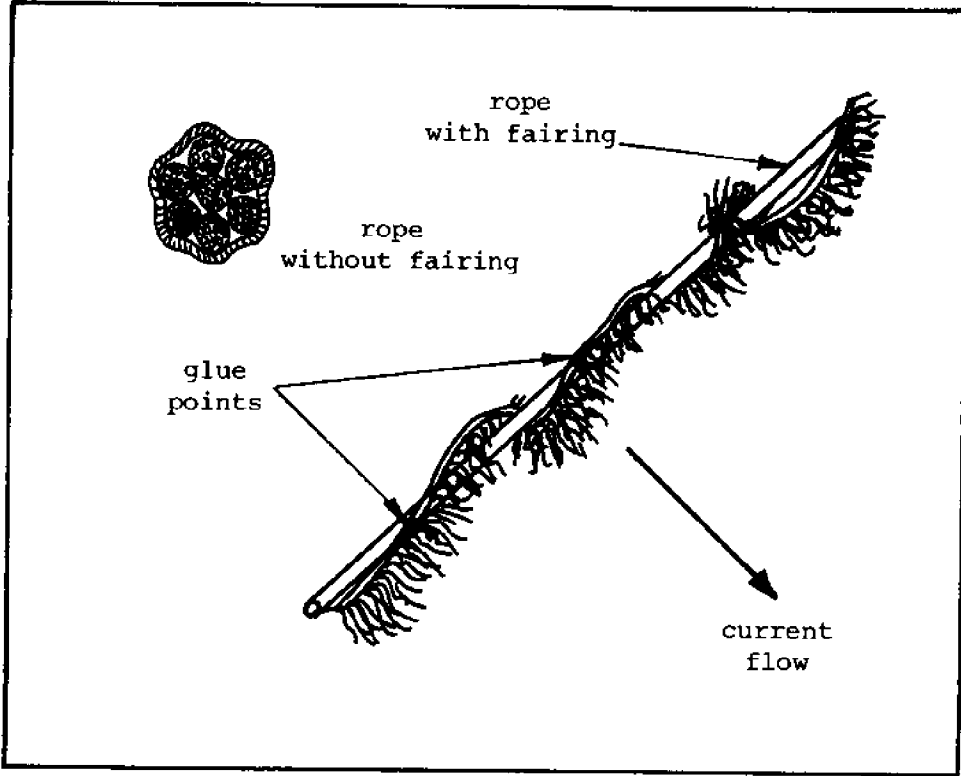


FIGURE 10.4 The Philistran Anti-Strumming Cable

to hold the ropes a fixed distance below the surface with weights attached below the cable.

To test more than one cable in one day of testing a length of line and a "come-along" winch was used to take the load while the test rope was being replaced.

The boats carrying the experiments and the instrumentation were anchored so that they remained just downstream of the cable.

#### 10.1.2 Cables Tested

The cables tested in this study were as follows:

1. 7/16" diameter Samson "Blue Streak"; 12 strand, single braid polyester and polypropylene rope.
2. 7/16" diameter Samson "Stable Braid"; a special braided polyester rope.
3. 3/8" diameter "phillystran" Kevlar rope; a special high strength low extension rope with polyurethane jacket.

Technical details of the cables are presented in Table 10.1. Two series of tests were also conducted with anti-strumming fairings. In the first of these tests a 50 ft. section of 4 inch pleated tape was stapled to the test section of the "Blue Streak" rope, as in Figure 10.3. In the second series of tests a rope with special anti-strumming fairings, supplied by the Philadelphia Resins Corporation, Figure 10.4, was inserted in the test section.

#### 10.1.3 Instrumentation

The instruments required for the strumming experiment were:

1. A current meter to measure the water velocity.
2. A load cell to measure the cable tension.
3. An instrument for measuring the frequency and the amplitude of the cable movement.

The current velocity was measured with a "Bendix" Savonius Rotor Current Meter. This device was suspended from the boat just downstream of the test section of the cable.

A strain gage load cell was used to measure the cable tension, Figure 10.5. This cell was milled from an aluminum bar to provide a safe load carrying capacity of 1,000 lb. Two strain gages were placed on each side of the aluminum bar, one active and one temperature compensating. The read-out for the load cell was a portable "Vishay" 1011 Strain Gage Reader. The load cell and gage reader system was calibrated by suspending known weights from the load cell. To observe the a.c. changes in the cable tension an additional amplifier was constructed with a gain of 7,500. The tension fluctuations were measured using a battery operated oscilloscope. This arrangement was also calibrated with known forces.

The measurement of amplitude and frequency proved to be the most difficult instrumentation problem. The following three methods were tried:

1. A sonar method using a pulsed 200 kHz signal.
2. A photographic method using a super 8 movie camera in a waterproof housing.
3. A mechanical/electrical system attached to the cable.

Sonar method was developed in the laboratory to measure the movement of cables in a tank. The transducer was suspended below the cable and shrouded to produce a narrow-angle vertical beam. The return signal from the rope was displayed on a battery operated oscilloscope. Laboratory experiments indicated that the reflections from surface waves were troublesome. A sound absorbing material floated at the surface was found to eliminate this problem in the laboratory.

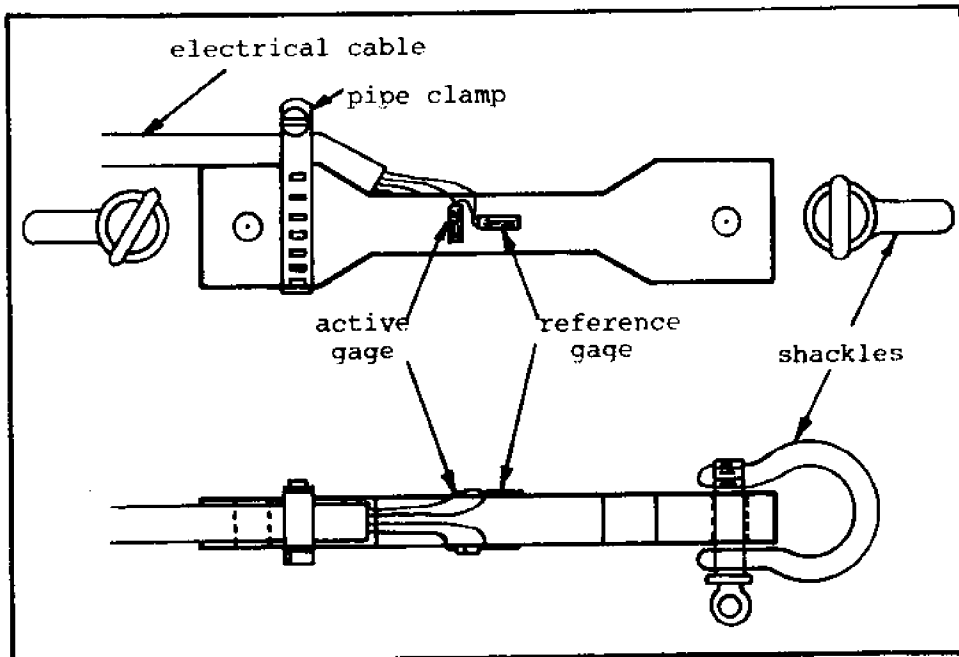


FIGURE 10.5 The Cable Tension Load Cell

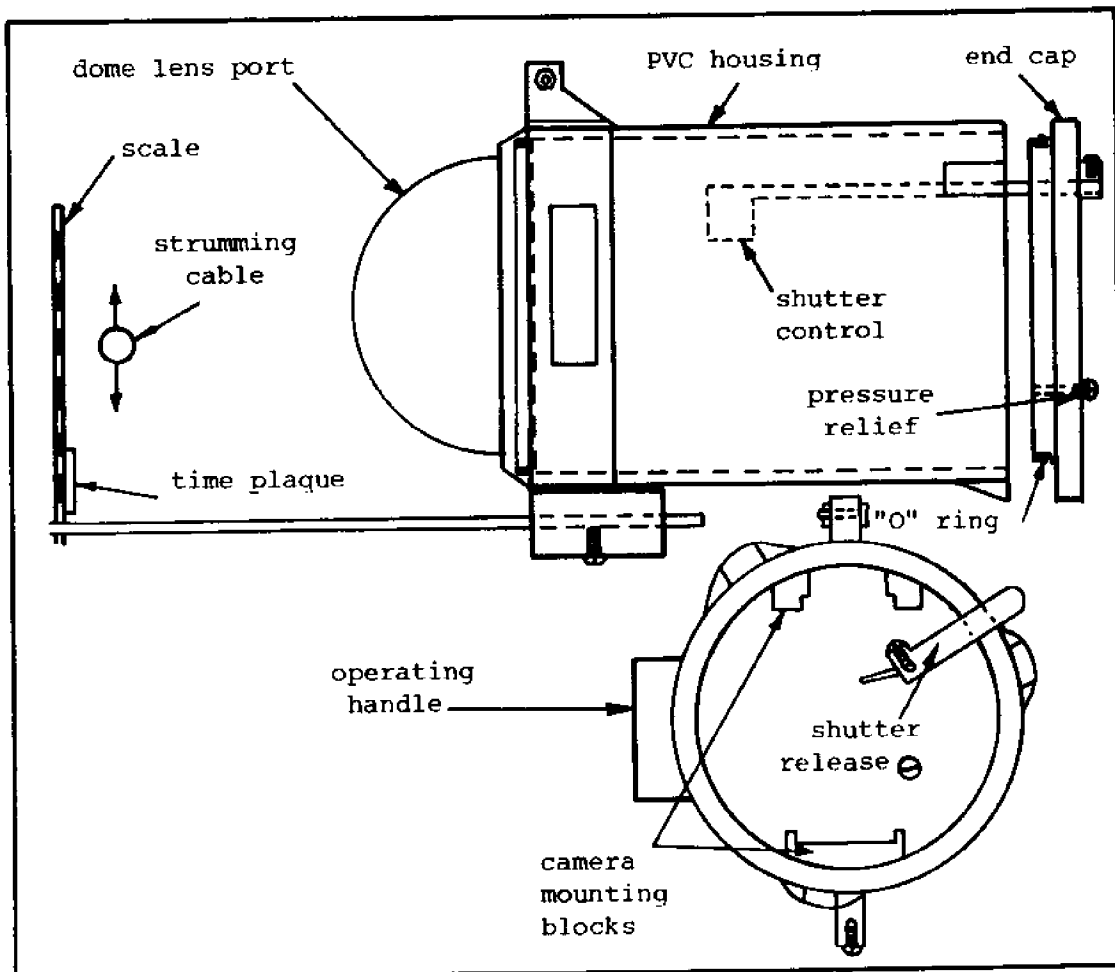


FIGURE 10.6 The Movie Camera Housing

An underwater movie camera system was developed to measure and record the frequency and amplitude of the strumming cable. The Honeywell Elmo super 8 movie camera was housed in a six inch diameter PVC tube, Figure 10.6. A "plexiglass" dome was placed at the front of the tube and sealed with an "O" ring. A flat 1/2 inch plexiglass plate was placed at the rear of the tube and also sealed with an "O" ring. PVC blocks were glued to the inside of the tube to brace it and allow it to slide in and out of the case. A brass rod with a lever arm penetrated the rear plexiglass plate to engage with the camera controls. Rotation of the lever started the movie camera.

An adjustable aluminum L shaped rod was attached to the side of the camera housing to provide a scale to facilitate the amplitude measurement. The focal length of the camera lens was varied with a series of close up lenses to position the reference scale bar approximately 18 inches from the camera lens.

The camera system was originally equiped with a 6 volt sealed beam unit to provide illumination for the cable. Batteries for the light were placed in the camera housing. Initial testing showed that there was sufficient ambient length and the lighting system was removed.

Kodak 4X super 8 movie film was used, with an aperture of 5.6. To develop the film three foot sections were pulled out of the cartridge, out-off and developed in Dektol (1:1) for 20 seconds. After fixing, washing and drying, the short sections were spliced together. The process took about 2 hours per cartridge; and although a negative film was produced, the procedure was much quicker than commercial processing.

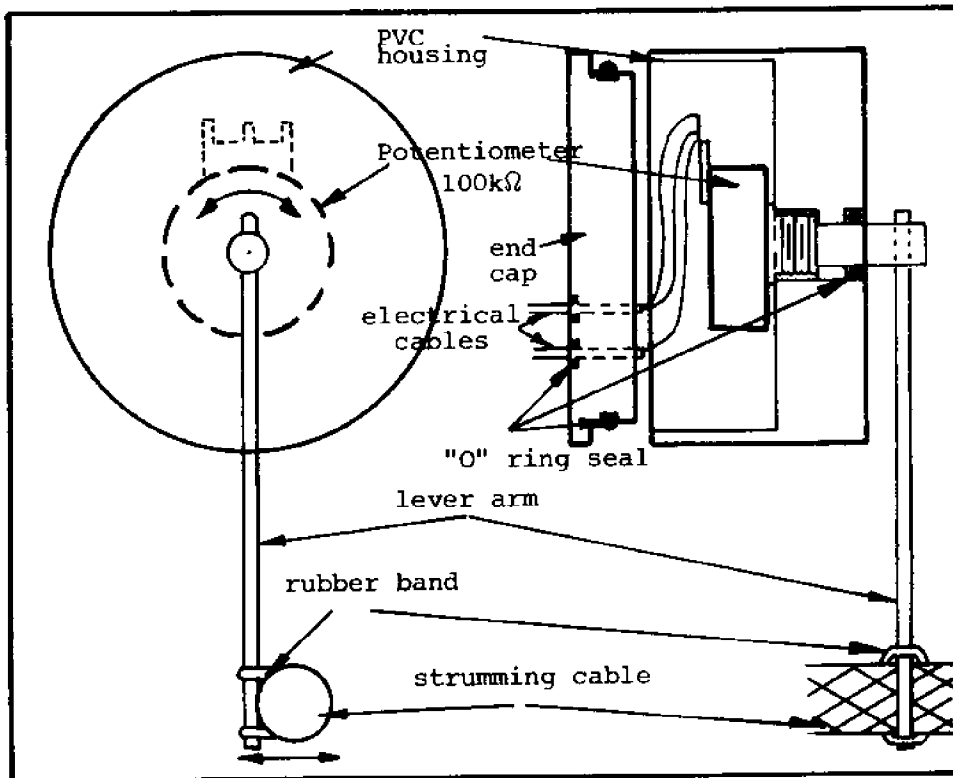


FIGURE 10.7 The Strumming Amplitude Transducer



Initial tests in the cable strumming experiment at the sandbar had showed that there was considerable energy in the strumming phenomenon and it was difficult to restrain a strumming cable. This fact suggested that a low friction and low inertia device could be attached to the cable with negligible reduction of the strumming amplitude.

A very simple amplitude transducer designed and built which utilized a 100 K potentiometer to measure the amplitude and frequency of the strumming cable. A 6 inch lever arm was attached to the potentiometer shaft and the outer end of the lever was fixed to the cable by means of a rubber band. In this way the movement of the cable resulted in a variation in potential at the potentiometer. The potentiometer was sealed in a small PVC tube using "O" rings to prevent leakage of seawater at the electrical cables, the potentiometer shaft, and the end caps, Figure 10.7. The instrument was calibrated by monitoring the output for known movements of the arm. In the cable strumming tests the output from the instrument was recorded on the FM cue channel of a "Nagra", three-channel tape recorder. One of the other channels was used for commentary of current velocity, tension, and time.

#### 10.2 THE TEST PROGRAM

The initial phase of the experimental program was the development of the test procedure. Various methods of setting up the cables were tried and the methods shown in Figure 10.1 and 10.2 were considered to be the most satisfactory.

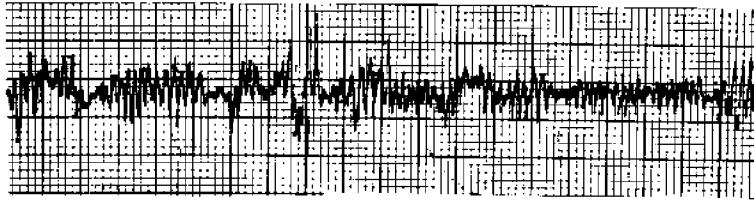
The acoustic method of determining cable amplitude and frequency was first tried but found to be very difficult to use. The transducer was required to be directly under the cable and this was almost impossible to achieve because the catenary of the cable varied with fluctuations in current velocity.

The movie filming technique was also used during the early experiments and although it did indicate the main features of the phenomenon it was discarded in favor of the direct measurement of cable amplitude and frequency using the potentiometer system. The main problem with the filming procedure was that the movie camera used in the experiments could only operate at 18 and 24 frames per second while the strumming frequency was approximately 10 Hz. It was therefore difficult to determine the cable amplitude when only two or three shots were taken per cycle of oscillation. In addition, the film processing was very time consuming. In the early experiments the strumming frequency was measured by allowing the cable to tap against a crystal microphone.

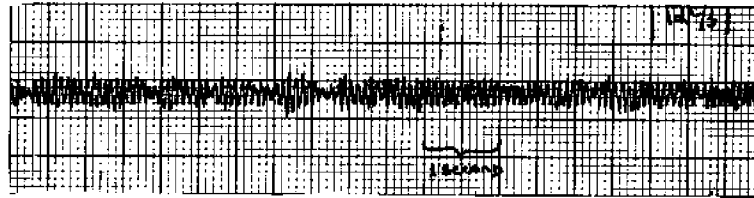
The main series of experiments were conducted with the amplitude transducer held downstream of the cable by an operator in a small boat. The current meter was also suspended from the boat with the recording instrumentation in the boat.

The cable was set up at low tide and tensioned, the recording of velocity and potentiometer output were made on the rising tide at suitable intervals until the velocity approached zero at the turn of the tide, results were sometimes also recorded on the falling tide.

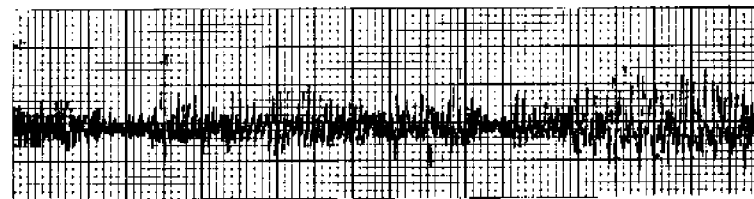
At the end of each day of testing the tape recorder results were played back through an oscilloscope to obtain preliminary results.



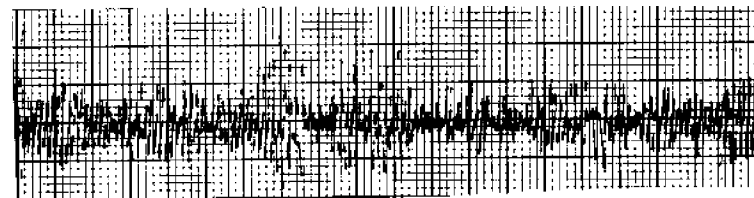
50 ft. of "Blue Streak"  
current - .5 kts  
freq. - 9.5 Hz  
mean amp - .19 inches



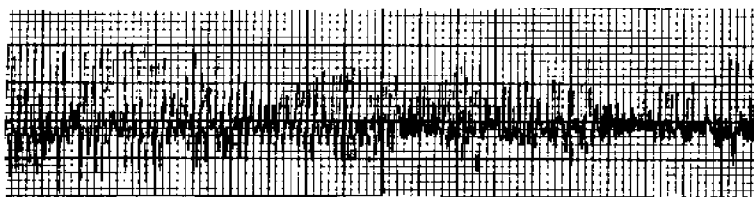
50 ft. "Blue Streak"  
current - .7  
mean amp - .12  
freq - 11.6



50 ft. "Blue Streak"  
current - .8  
mean amp - .13  
freq - 11.75

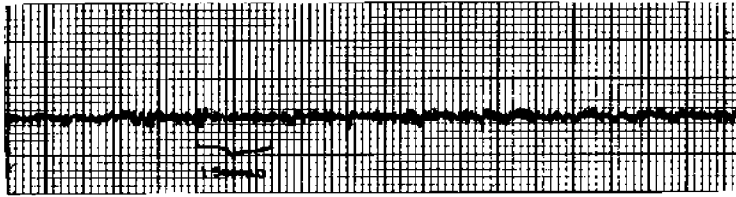


50 ft. "Phillystran"  
current - .69  
mean amp - .24  
freq - 13.5

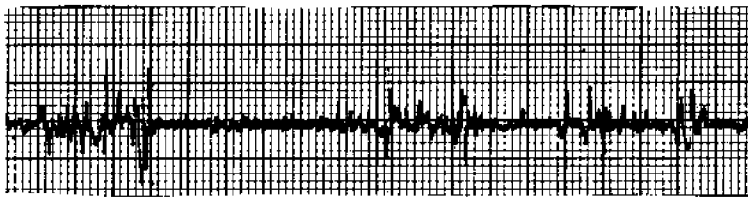


50 ft. "Phillystran"  
current - .51  
mean amp - .21  
freq - 11

FIGURE 10.8 Examples of Amplitudes Transducer Signals



50 ft. "Phillystran"  
with fairing  
current - .55 kts  
freq - 40-100 Hz  
amp - 0. inches



50 ft. "Blue Streak"  
with fairing  
current - .75  
mean amp - .13  
freq - 6.5

FIGURE 10.8 (cont.) Examples of Amplitude Transducer Signals

More complete analysis of the results were made later at M.I.T. using data processing instrumentation available there.

Tests were conducted using the various types of 7/16" rope described earlier. In addition two lengths of rope with anti-strumming fairings were placed in the test cable and evaluated. In the first of these fairings a 50 ft. section of pleated tape was stapled to a nylon rope, as shown in Figure 10.3. The purpose of this experiment was to examine the problems of experiments with faired cables. No difficulties were encountered. A 50 ft. sample of a cable with a large anti-strumming fairing, as shown in Figure 10.4, was made available at short notice and placed in the test section. The characteristics of this cable system were also determined.

### 10.3 THE EXPERIMENTAL RESULTS

The main results were put onto the tape recorder in the form of amplitude transducer results together with voice commentary giving details of current velocities and so forth. At M.I.T. the amplitude transducer results were played back through a single-channel paper recorder to obtain charts of the data. The signals were passed through a low pass filter to eliminate low frequency movements of the operator holding the amplitude transducer. Examples of the records are shown on Figure 8. These results showed that the amplitude of strumming was not uniform but varied with time. The records also indicated that the anti-strumming fairings on the Phillystran rope eliminated strumming at the test conditions. The graphical output of the transducer signals was used to determine:

1. The average amplitude.
2. The peak amplitude.

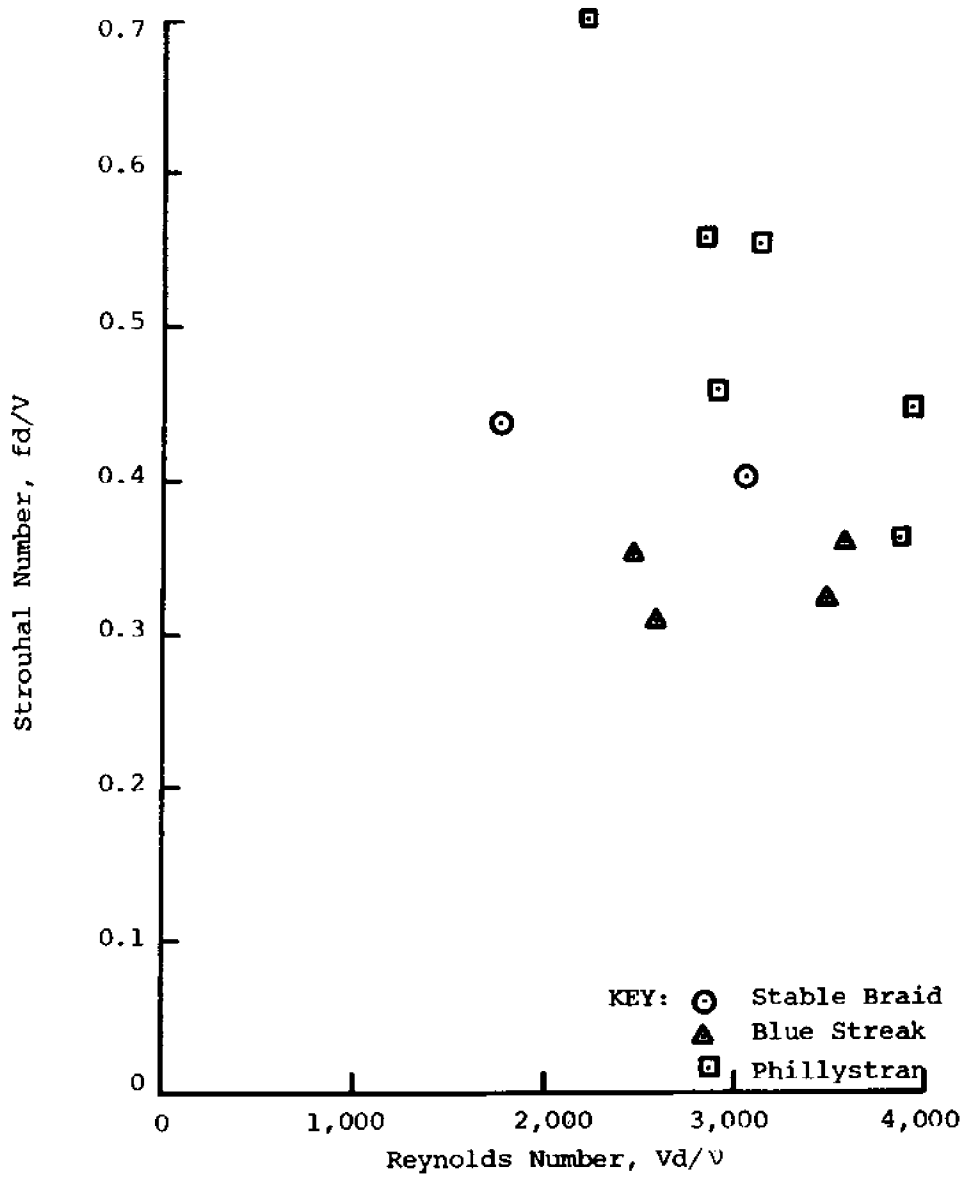


FIGURE 10.9 Cable Strumming Experiments, Strouhal Number, Reynolds Number Measurements

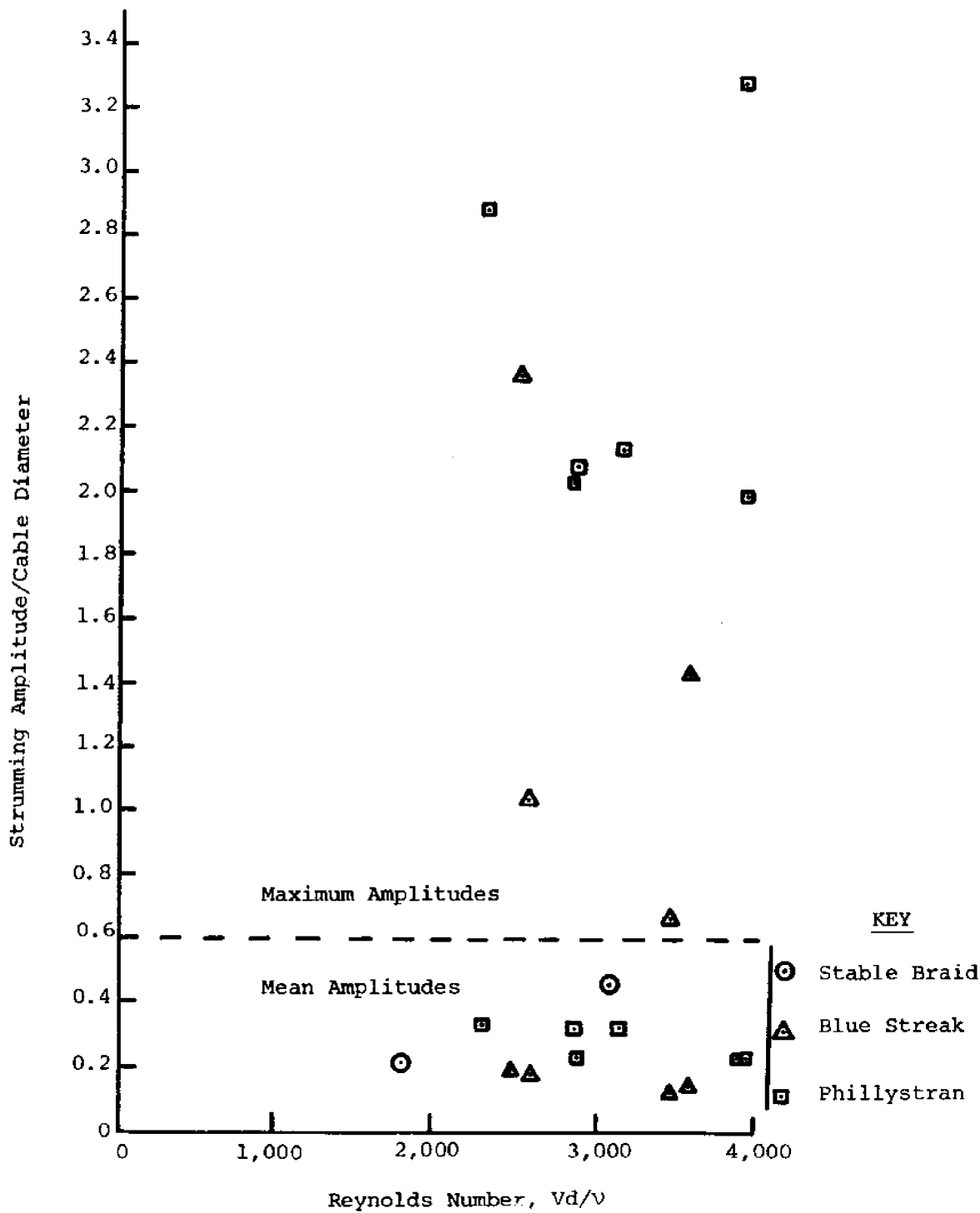


FIGURE 10.10 Cable Strumming Experiments, Amplitude, Reynolds Number Measurements

3. The standard deviation of the amplitude.
4. The main frequency of strumming.
5. The Strouhal number.

These results are presented in Table 10.2 and on Figures 10.9 and 10.10.

Samples of the amplitude transducer output were also processed using a frequency-amplitude analyzer. This instrument provided charts giving the r.m.s. amplitude plotted against frequency, Figures 10.11a-f. These figures showed that although the highest amplitude was at the first or fundamental frequency, in addition there were appreciable amplitudes at the second and higher harmonics. The cables with anti-strumming fairings were the exceptions to this generalization.

The measured tensions during the tests were in the range 200-500 lb. The high frequency fluctuations in tension were not measured with acceptable accuracy.

The measured values of Strouhal numbers and the amplitude/diameter ratios for the range of Reynolds numbers for the various cables are presented on Figure 10.9 and 10.10.

#### 10.4 CONCLUSIONS AND RECOMMENDATIONS

##### 10.4.1 Conclusions

Preliminary measurements of the amplitudes and frequencies of strumming cables have been carried out in a field test in the ocean. The strumming action was found to be very strong and energetic. The amplitudes and frequencies of the cables were measured by means of a very simple transducer which appears to give excellent results. These results are



presented in Table 10.2 and on Figures 10.9 and 10.10 of this report. The measured Strouhal numbers were higher than the value of 0.2 that appears in the literature.

Tests were also conducted using cables with anti-strumming fairings. The first fairing tested was constructed by attaching a 50 ft. length of 4 inch wide pleated tape to a cable. This device appeared to have a slight influence on the cable strumming. The second fairing tested was a specially constructed anti-strumming fairings attached helically around the cable. Experiments with the system showed that strumming was essentially eliminated at the range of water speed tested. However, the fairings increased the effective diameter of the cable and had a much higher drag than the bare cable.

#### 10.4.2 Recommendations

The tests conducted during the preliminary study were over rather limited ranges of cable diameters and water current speeds. Future tests should be conducted with larger and smaller cable diameters to increase the range of test Reynold's numbers.

The tests on anti-strumming fairings should be extended to other designs.

Table 10.1 Ropes Tested in the Strumming Experiment

1. Samson "Blue Streak"

12 strand, single braid, polyester and polypropylene (half and half), 7/16" nominal diameter, 0.39 inch measured diameter under tension, specific gravity 1.14, breaking strength approximately 5,000 lbf.

2. Samson "2 in 1 Stable Braid"

Braided polyester (Dacron) cover - braided polyester core, 7/16" nominal diameter, 0.39 inch measured diameter under tension, specific gravity 1.38, breaking strength approximately 5,800 lbf.

3. Philedalphia Resin Corporation "Phillystran" PS29-C39J

Construction 7 x 7 (PS29-B105) "Kevlar" rope with a polyurethane jacket, 3/8" nominal diameter, 0.45 inch measured diameter over the jacket, specific gravity approximately 1.2, breaking strength 17,000 lbf.

Table 10.2 Experimental Data for Cables Strumming Tests

Current kts	Frequency Hz	Strouhal No.	Mean Amp inches	Stand.Dev- iation, inches	Max Amp inches	Mean Amp diam.	Max Amp diam.	Reynolds No.
STABLE BRAID:								
.62	13	.4	.47	.22	--	1.205	--	3,100
.36	8	.43	.21	.11	--	.536	--	1,800
BLUE STREAK:								
.52	8.5	.31	.18	.1	.41	.46	1.05	2,600
.5	9	.35	.19	.1	.93	.49	2.38	2,500
.72	13.5	.36	.14	.08	.56	.36	1.44	3,600
.7	11.6	.32	.12	.03	.26	.307	.67	3,500
PHILLYSTRAN:								
.51	11	.46	.21	.12	.92	.47	2.04	2,940
.68	11.5	.36	.21	.22	1.48	.47	3.29	3,920
.55	14	.55	.36	.18	.96	.80	2.13	3,173
.69	14	.44	.24	.12	.89	.53	1.98	3,981
.5	13	.56	.33	.18	.93	.73	2.07	2,885
.4	13	.7	.32	.22	1.3	.71	2.89	2,308
BLUE STREAK & FAIRING (FIGURE 3):								
.75	6	.15	.13	.17	.56	.33	1.44	3,750
.78	6.5	.16	.12	.1	.37	.31	.95	3,900
.8	11.75	.28	.13	.12	.93	.33	2.38	4,000
.8	12.5	.3	.22	.14	--	.56	--	4,000
PHILLYSTRAN Y FAIRING (FIGURE 4):								
.55	--	--	.04	--	.26	--	--	--

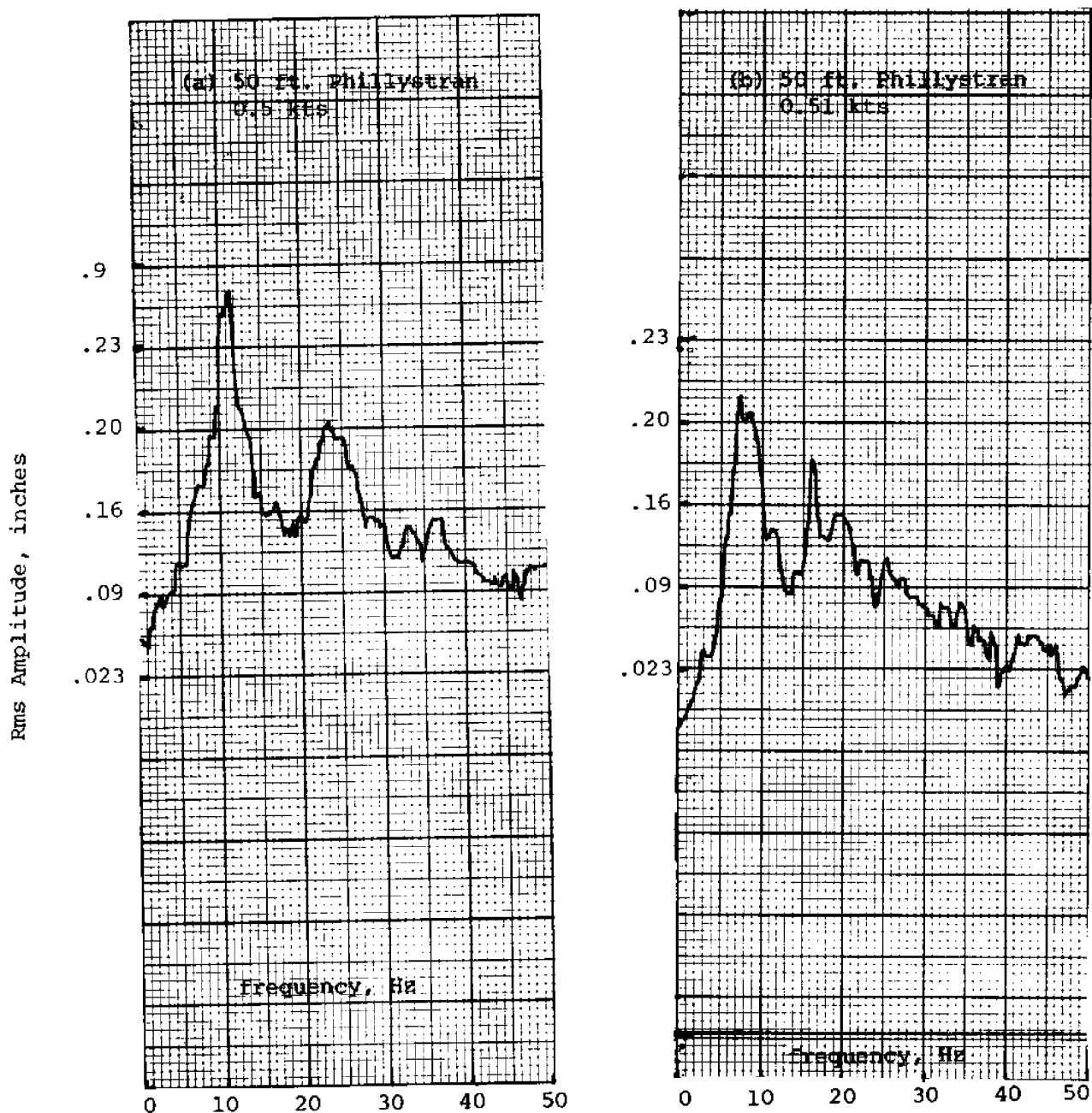


FIGURE 10.11 Examples of Analyzer Output,  $\frac{1}{2}$  Hz Steps

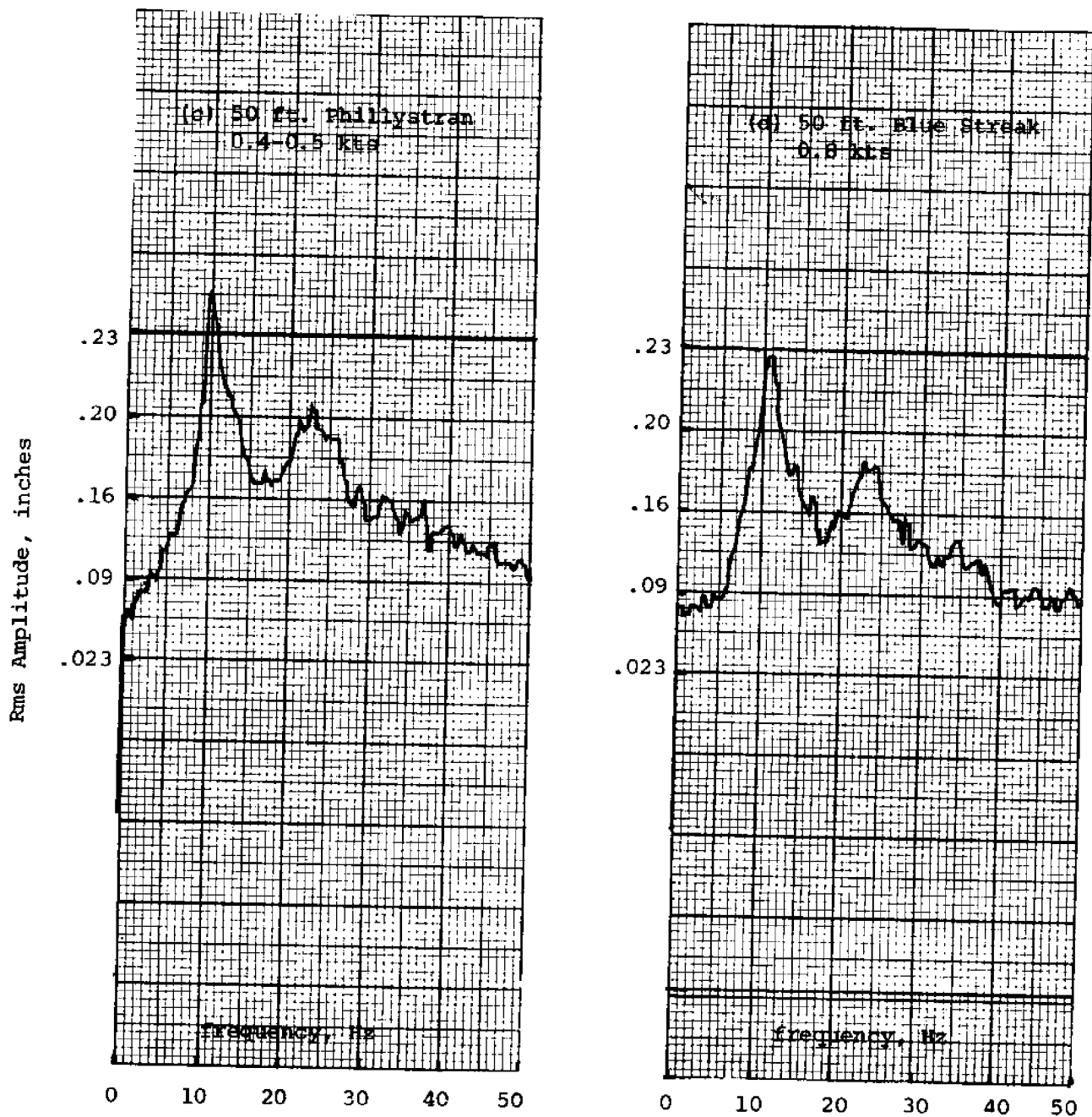


FIGURE 10.11 (cont.)      Examples of Analyzer Output,  $\frac{1}{2}$  Hz Steps

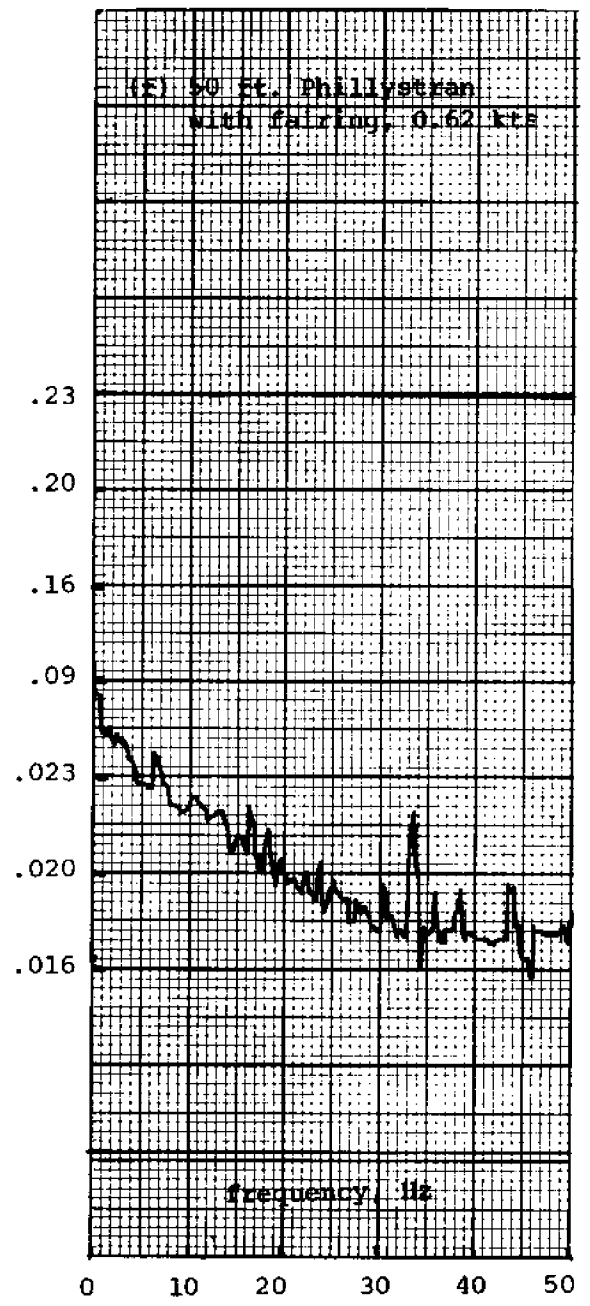
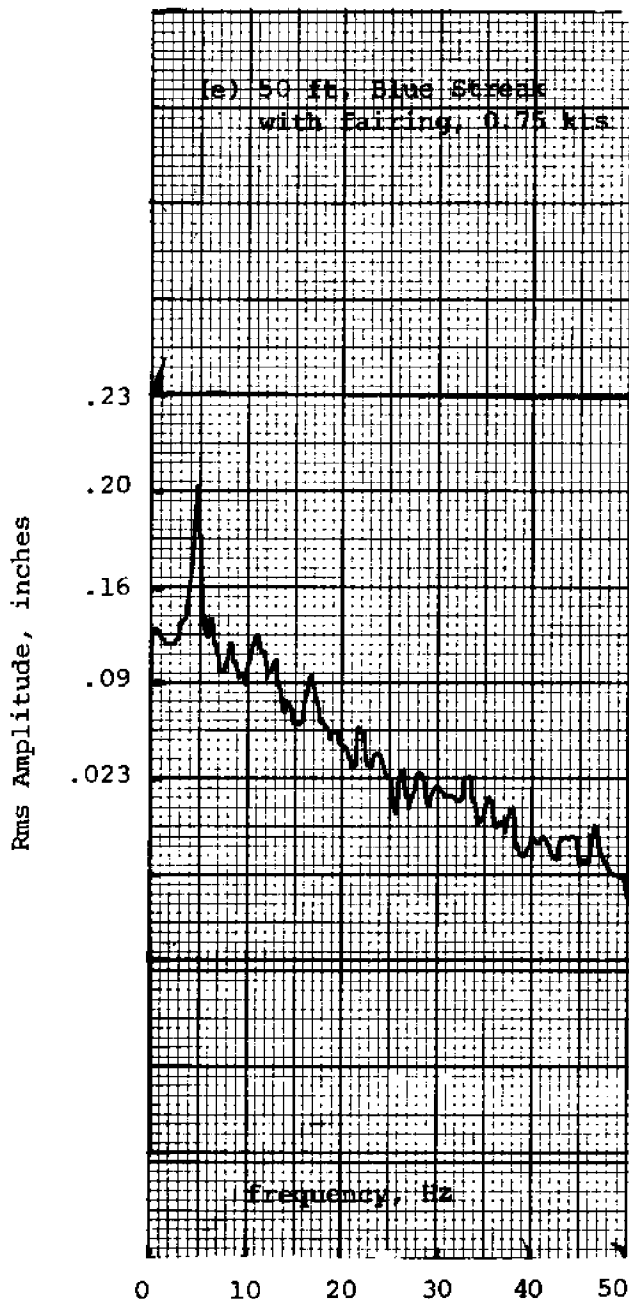


FIGURE 10.11 (cont.) Examples of Analyzer Output,  $\frac{1}{2}$  Hz Steps

## 11. AN ELECTROMAGNETIC UNDERWATER COMMUNICATION SYSTEM

In recent years, there has been a steady increase in scientific and industrial activity underwater. This has brought with it a growing need for a simple and reliable method of underwater communications. Acoustic communications has been used extensively in underwater work, but limited bandwidth and susceptibility to interference from noise, scattering and reflections tend to limit its usefulness. Ordinary electromagnetic radiation is relatively free from this sort of interference, but it attenuates rapidly in water except at very low frequencies, where it has been used for submarine communications.

During World War II, the U.S. Navy investigated a short range communications system using audio frequency currents fed through the water. A dipole antenna, consisting of two electrodes separated by a short distance, was used to establish the current, and a similar dipole was used to detect the electric field produced. Although the final report was optimistic about the usefulness of such a system, the Navy apparently abandoned it for unknown reasons.

This system of communicating was apparently rediscovered in 1964 by Minto, who made a number of claims about its effectiveness. Although he was secretive about his system, his equipment was very similar to the type used by the Navy in the 1940's, and it is reasonable to assume that Minto was dealing with the same effect. Despite his original claims, Minto also appears to have abandoned work on this system.

The purpose of this project was to determine, first by theoretical analysis and then by experimental measurements, exactly how

well this type of communications works. Once the characteristics of the system are understood, it should be possible to determine if the system has any advantages over acoustic systems, and possibly why it has been abandoned twice despite impressive claims as to its effectiveness.

The theoretical derivation is not given here but appears in Ref. 11.1.

#### 11.1 EQUIPMENT DESIGN

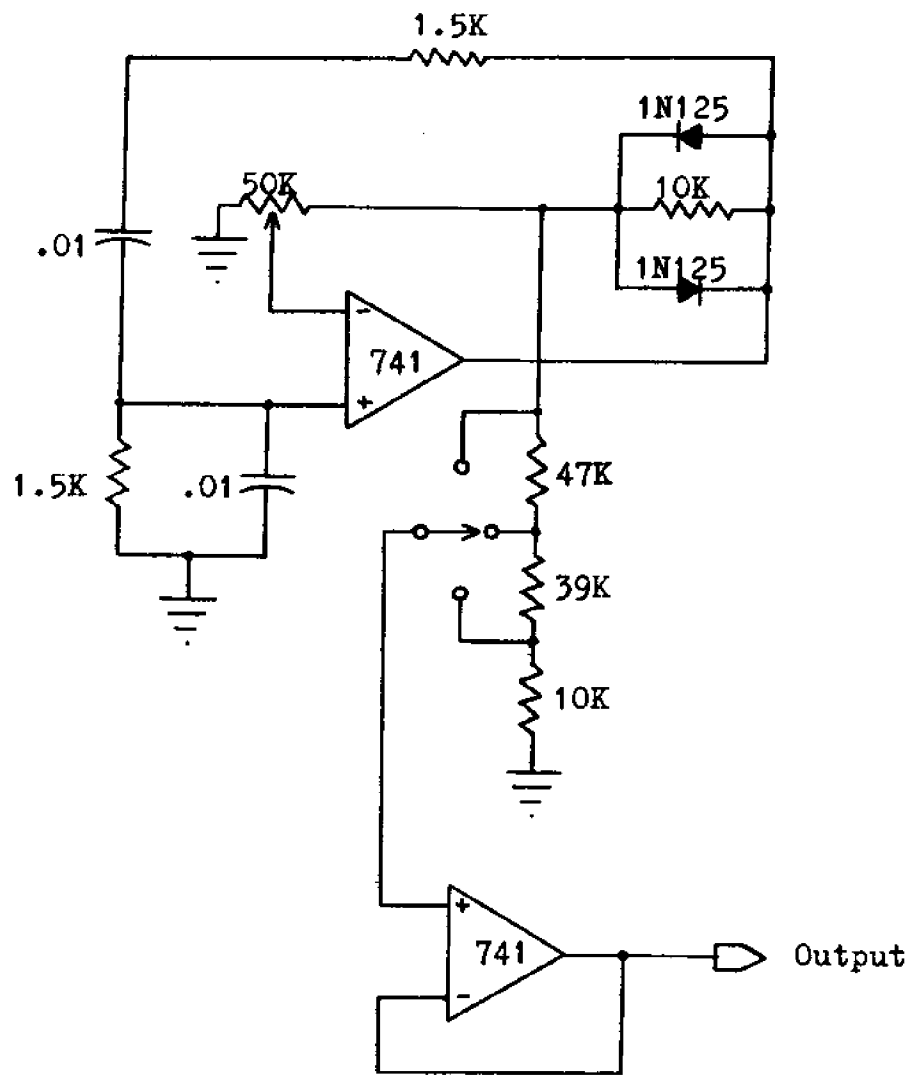
Before any serious transmitter or receiver designs could be worked on, it was necessary to measure the characteristics of various antenna designs. This assisted in selecting an optimum antenna structure, and in properly matching the transmitter design to the antenna impedance.

From theoretical considerations (Ref. 11.1) the equation for the voltage developed across the receiving antenna shows a linear increase with both length and driving current of the transmitting antenna. For maximum efficiency, it is desirable to have as low an antenna impedance as possible. At a fixed current level, and therefore a fixed voltage at the receiver, halving the antenna impedance halves the power drain on the transmitter.

Measurements were taken of antenna impedance as a function of length, electrode area and driving frequency. The length and area measurements were made at 1 KHz using an impedance bridge. The frequency measurements were carried out by displaying the actual voltage current curves on an oscilloscope using a buffered signal generator and a current probe.

Once the length of the antenna is greater than a few times the electrode dimensions, the impedance increases fairly linearly with





Power:  $\pm 9$  volts

FIGURE 11.1 10KHz Fresh Water Transmitter

increasing length. However, due to a large offset in the curve at low values, it requires less power to produce a given field strength with a long antenna than with a short one. Therefore, antennas should be made as long as conveniently possible for maximum efficiency.

It was found that increasing the antenna electrode area beyond three or four square inches (using copper sheet) gave only a very small decrease in impedance. At a fixed length, there appears to be a lower limit to antenna impedance which can be closely approached with only moderate sized electrodes. One and one half inch diameter copper pipe was chosen for the electrodes to give as much area as possible in a reasonably small volume.

Antenna impedance was almost purely resistive and fairly constant at high frequencies (greater than KHz). However, electrochemical effects at lower frequencies give a rapid increase in resistance and phase shift. If a dc measurement is taken with a regular ohmmeter, the reading will drift fairly rapidly up to a considerably higher value than the same antenna at 1 KHz. For this reason, transmission should be at frequencies higher than at least 100 hz, and a.c. coupling to the antennas should be used at all times.

The final antenna design chosen for salt water use consisted of a one meter long piece of 1/2 inch lucite rod with electrodes made from three inch long sections of the copper pipe, mentioned earlier. This resulted in an impedance just under two ohms at 1 KHz. The antennas used for the freshwater experiments were ten inches long, with one and one quarter inch square copper sheet electrodes. These had an impedance of about 700 ohms at 1 KHz.

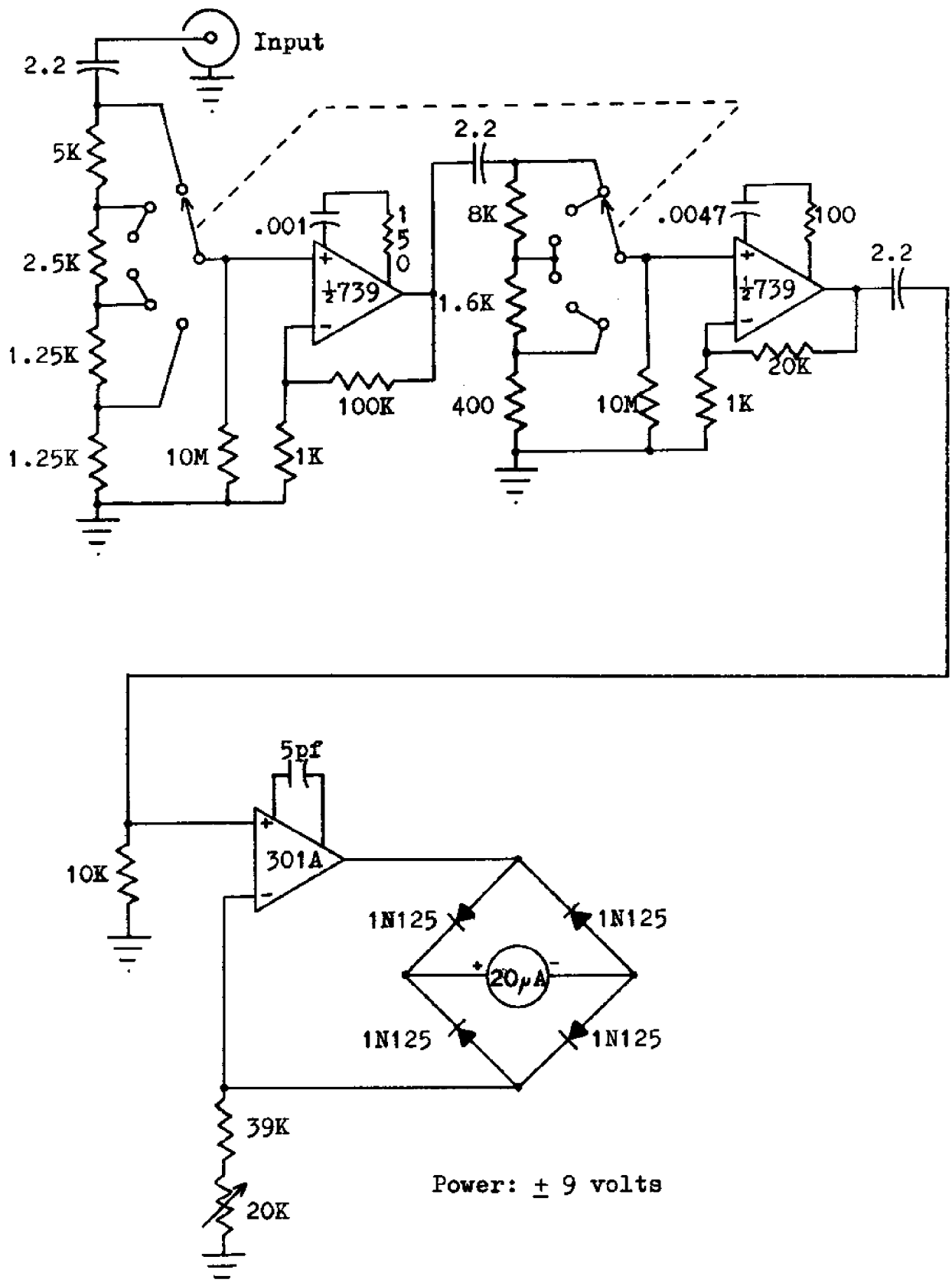


FIGURE 11.2 Salt Water Receiver

The receiver used for the freshwater measurements was a commercial a.c. voltmeter. The unit used could measure voltages down to .1 millivolt full scale, at frequencies up to 4 MHz.

Two different transmitters were used for the freshwater experiments. The first was made by using an audio amplifier as a buffer amplifier for a commercial audio signal generator. This was the same system used for the antenna frequency measurements. The second transmitter was made with two 741 operational amplifiers; one as a 10 KHz oscillator, and the second as a buffer amplifier, Figure 11.1. This was housed in a small water tight PVC cylinder, and was battery powered to eliminate power cables from the surface.

The saltwater receiver was designed to be similar to the a.c. voltmeter used in the freshwater experiments, but with a watertight housing. The circuit uses a 739 dual low noise operational amplifier as a two stage amplifier, and an LM301A operational amplifier for the voltmeter circuit, Figure 11.2. The circuit was mounted in a four inch PVC cylinder with a clear one inch lucite end cap to allow reading the meter underwater.

The saltwater transmitter used an oscillator and buffer stage similar to the one in the small freshwater unit, but tuned to 1 KHz. This was used to drive a voltage controlled current source with a ten to one current transformer on the output, Figure 11.3. The circuit was also housed in a four inch PVC cylinder, but with an aluminum heatsink on one end to provide cooling for the power stage. Although cooling was not necessary at the power levels the batteries can supply, the circuit was designed for power levels up to 10 watts if later experiments require it.

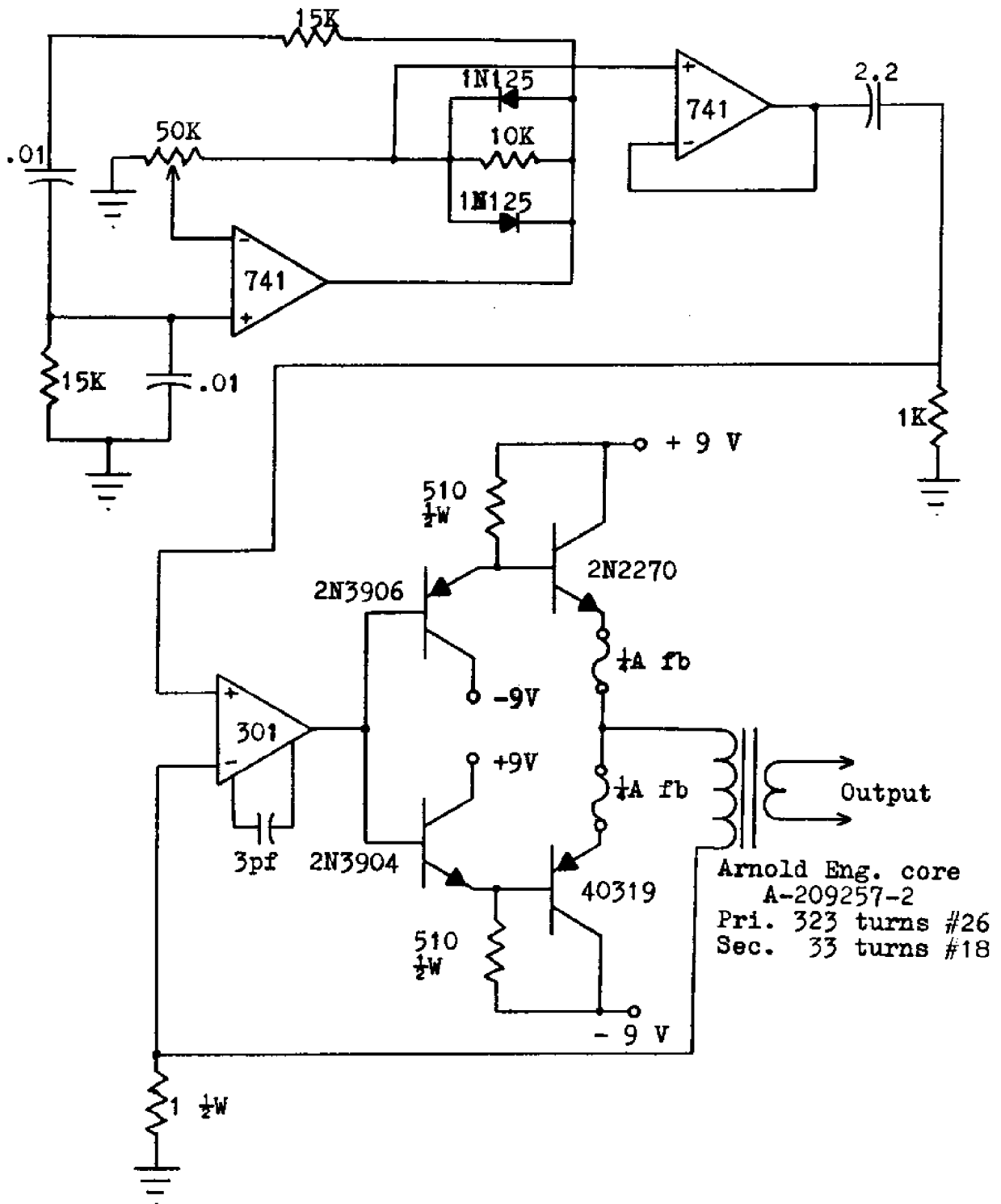


FIGURE 11.3 1 KHz Salt Water Transmitter

All of the underwater connections were made by sealing metal phono plugs with epoxy, and then sealing the mated connectors with soft PVC tubing sleeves held in place with hose clamps. The actual cylinders were sealed with O-rings, and the switches (including the rotary switch on the saltwater receiver) were sealed with commercial switch seals.

## 11.2 EXPERIMENTAL PROGRAM

Several experiments were carried out in the M.I.T. swimming pool to begin checking the various characteristics of the system. Detailed antenna pattern measurements were made, and the effects of antenna length and depth were investigated. A test of the frequency response of the system was attempted, but problems with the cables leading down to the antennas from the surface prevented any conclusive results.

The antenna pattern measurements were made by mounting a fixed receiving antenna on the bottom, connected to the a.c. voltmeter at the surface. The small 10 KHz transmitter was then placed on the bottom and rotated. The results of the measurement for the transmitting and receiving antennas in the same plane is shown in Figure 11.4. The measured values match the theoretical pattern fairly closely. Variations are probably the result of noise and the antennas shifting slightly on the bottom. The results for the transmitting and receiving antennas in perpendicular planes also have the proper angular dependence, and the maximum field was about half as strong as for the previous case, as predicted.

Increasing the length of the transmitting antenna did increase the field strength, but the antenna voltage was constant, not the current, so the changing impedance reduced the effect somewhat. A current source

KEY:

—— Measured

----- Theoretical

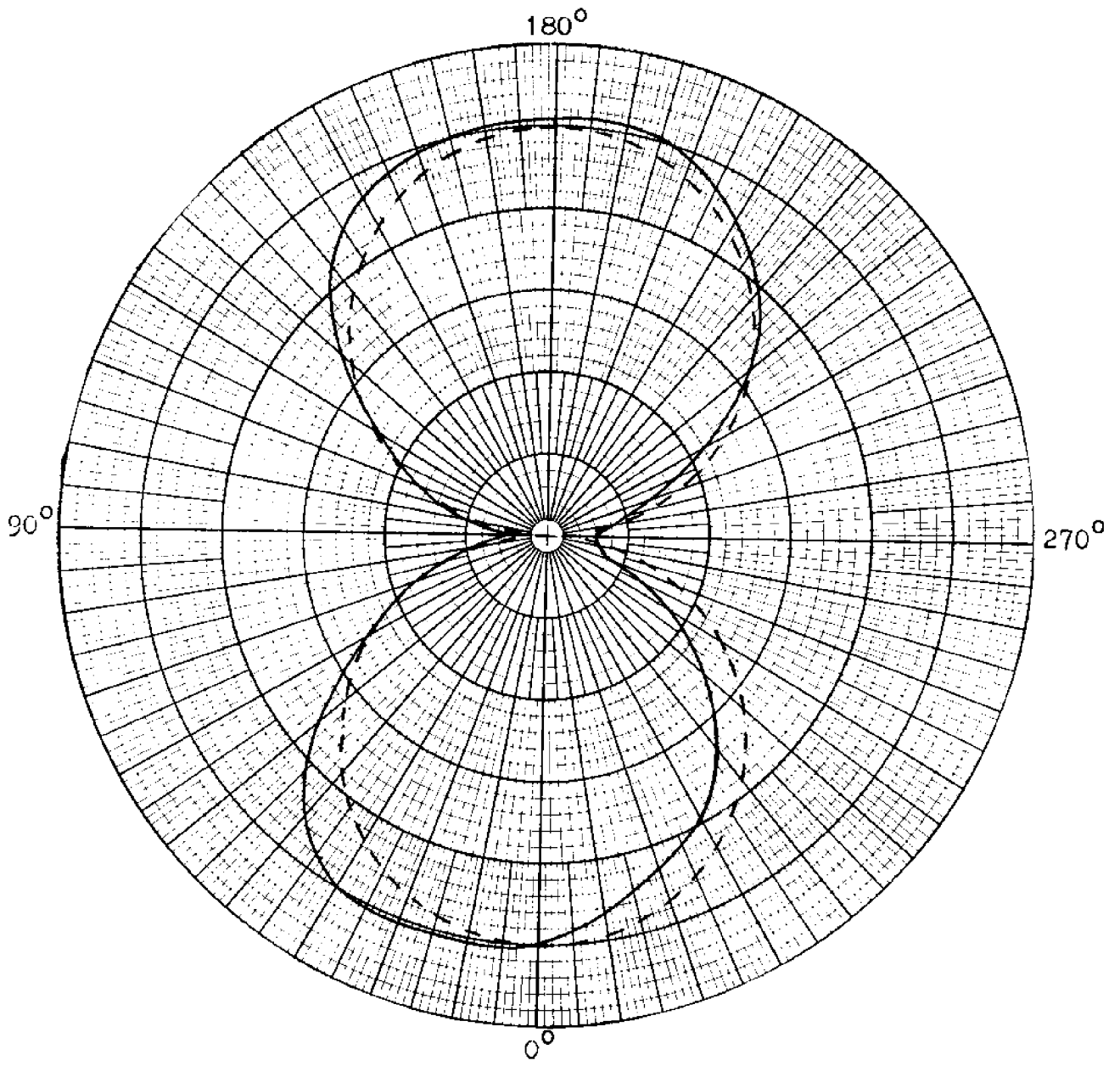


FIGURE 11.4 Antenna Pattern for  $\theta' = 0$

transmitter would have eliminated the problem, but one was not available at the time.

The antenna depth measurements were obtained by sliding the antennas up and down lucite stands sitting on the pool bottom. With the antennas separated by five feet, no noticeable effect on the field strength was measured until the antenna was less than two feet from the surface or bottom.

Two experiments were to be made in salt water. The first was to be a measurement of the effect of depth at several distances, and the second was to be a measurement of attenuation as a function of distance. Unfortunately, after a successful check of the saltwater transmitter and receiver near shore, when the equipment was tried at the dive site the next day, no readings could be obtained at all. The causes of this malfunction has not been determined yet, and further tests have been temporarily suspended until the problem has been located and eliminated.

#### 11.3 CONCLUSIONS AND RECOMMENDATIONS

It is difficult to draw any major conclusions at this point, except that this research should be continued. The failure of the salt-water equipment has left a large gap in the experimental results which must be filled before any decisions can be made.

The theoretical analysis given in Ref. 11.1 indicates that this system should not work any better than any of the other electromagnetic systems that have been tried. It is possible that the good results claimed by other people can be traced to the effects of nearby boundaries on the system.



The only major successful experimental measurements taken so far were the antenna pattern tests. These matched the theoretical predictions quite closely.

The experiments which still need to be done are: 1) attenuation with distance, 2) detailed measurements of the effects of boundaries, 3) effects of frequency on transmission, 4) effects of antenna length on transmission and, 5) variation of field strength with current. Once all of these measurements are taken, it should be easy to determine if the theory is correct, and if the system has any important characteristics.

It is possible that although the system is worthless for normal communications, it may have other uses. The distortion of the fields near boundaries of changing conductivity may be useful for geologic analysis of the bottom, or for some of metal detector. There are a large number of possible applications to investigate once the communication one has been answered.

#### 11.4 REFERENCES

- 11.1 P. C. White, "Investigation of a Electromagnetic Underwater Communication System", B.S. Thesis, Electrical Engineering Department, MIT, January 1975.

## 12. A Savonius Rotor Power Generator

### 12.1 INTRODUCTION

The coasts of northern New England and the Maritime Provinces of Canada include many narrow estuaries in which the rising and falling tides induce moderate cyclic inward and outward flow velocities. Most of these estuaries, unlike Passamaquoddy Bay in Maine or the Minas Basin in Nova Scotia, have insufficient tidal height range and/or flow volume to make damming and application of water turbines economical, even if such damming were ecologically acceptable. The Bagaduce Narrows, near the Maine Maritime Academy campus and evaluated as part of the Summer Laboratory in 1973, provides tidal flow velocities in excess of three knots for the central two hours of the flood and ebb of each tide, or roughly seven hours per day. There are several sites, each within ten miles from the MMA campus, having significantly higher tidal velocities than those at Bagaduce Narrows. Except for semi-monthly variations related to the phases of the moon, such tidal flows are relatively constant throughout the year, and are insensitive to conditions of drought in summer or freezing in winter.

Last year a horizontal axis water propeller to harness the power of such flows was designed and built. In this year's experiments a Savonius rotor was used. While it is known that the Savonius rotor cannot compare in efficiency with a well-designed propeller, it was the conclusion of the authors that the Savonius rotor would be overall superior for this application.

In a size to produce 1,000 watts of power from a 3-knot water flow, four basic advantages are claimed for the Savonius rotor compared to a four-bladed propeller.

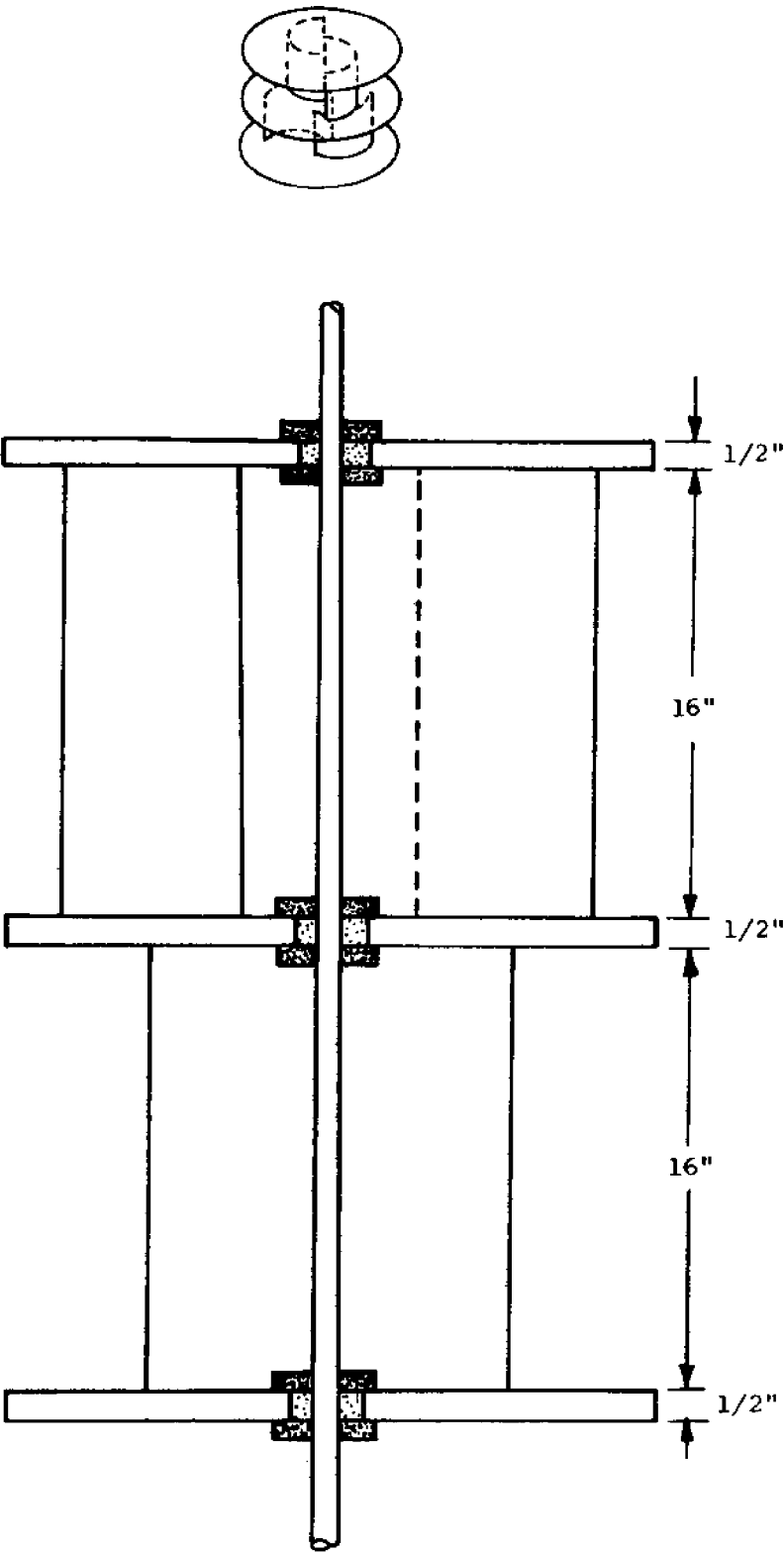


FIGURE 12.1 Savonius Rotor Power Generator

1. The Savonius rotor is more rugged, simpler, and easier to manufacture.
2. The efficiency of the Savonius rotor is less critically dependent on design details and blade-surface finish. It can operate reliably at water speeds as low as 0.03 knots.
3. The Savonius rotor is omnidirectional: it does not need to be reoriented as the tide reverses, and can readily accomodate frequent short-term changes in the speed and direction of the ambient flow.
4. The Savonius rotor has a vertical shaft axis, such that a generator mounted above the water surface can be driven without belts, gears, or pulleys. The vertical orientation also is predicted to simplify operational installation.

A simple Savonius rotor/generator installation is predicted to provide a potentially economical source of electrical power for the several thousands of locations in the immediate vicinity of tidal flows without requiring the ecology-altering concrete dams associated with larger more efficient installations.

#### 12.2 APPARATUS DESCRIPTION

A Savonius rotor of conventional design was constructed, Figure 12.1. Two coaxial two-bladed rotors, each 16 inches high and 11 inches in diameter were used. The rotor "blades" were sheets of 20-gauge galvanized steel. Three 13-inch-diameter plywood discs, each 1/2-inch thick, served as end plates, and as jigs for the curved rotor blades. The rotor was attached to a 1/2-inch steel shaft via three conventional TEK bearings.

A small AC generator was mounted coaxially with the rotor approximately 16 inches above the top of the rotor and, by assumption, above the surface of the water, eliminating the need for major waterproofing

of the generator. Electrical output from the generator was connected to a symmetrical current divider circuit comprising two rheostats. The ammeter measured one half of the total current output from the generator.

Attempts to design a simple, inexpensive, and rigid anchoring system for mounting the rotor in an actual tidal stream were discontinued midway through the study, primarily due to projected difficulties arising from a shortage of divers, most of whom were already committed to other projects. It was therefore decided to mount the rotor beneath the outboard-propelled catamaran constructed as a "mothership" for the robot submersible project. Use of the catamaran eliminated both installation, transportation, and design difficulties associated with the Bagaduce Narrows site, while allowing controlled variation of "tidal" flow velocity.

The rotor was mounted vertically midway between the bows of the catamaran with the top of the rotor approximately four inches below the waterline, and with the bottom of the generator 12 inches above the waterline. The "leading edge" of the rotor was approximately on a line between the bows.

#### 12.3 TEST PROCEDURES

Delays in completing both the rotor and the MIT submersible led to both projects requiring the catamaran simultaneously during the last week of the summer laboratory. Because the catamaran had been designed and built specifically for the submersible study, only two short tests of the rotor in operation could be scheduled. No problems were encountered in either of these sets of tests, but the brief test time available forced several procedural shortcuts which would not have been required otherwise.

The speed of the flow past the rotor was assumed to be that of the catamaran through the water. This is a possible source of error and is discussed later. The speed was estimated from the time required for the 15-foot catamaran to pass a floating block of wood; that is, velocity  $V = 15/t$  feet per second, where  $t$  is the time interval in which the floating block appears to move the length of the catamaran. The value of  $t$  was taken as the median value of three estimates made by three different observers aboard the catamaran. Rotor RPM values were estimated immediately before and after each speed estimate. Four catamaran speeds, represented by  $t$  values of 15 sec., 7 sec., 5 sec., and 3.5 sec. were used. All tests were run with the catamaran moving with a roughly 8-knot wind and an 8-inch to 12-inch choppy sea. Water depths were in excess of 40 feet for all tests.

Power output from the generator was estimated as  $P = (2I)^2 R$  where  $I$  represents the measured current from one-half of the current divider circuit. The total resistance,  $R$ , of the rheostat "load" was 23 ohms. The current output from the generator contained a low-frequency pulsating component; the recorded current values represent the "steady" AC plus approximately 50% of the (small) pulsation.

No attempt was made to estimate the efficiency of the generator; efficiencies were computed only for the rotor and generator as a combined unit. No attempts were made to optimize the rheostat resistance to maximize generator power output.

#### 12.4 TEST RESULTS

Results from the two test sequences are tabulated in Table 12.1. The efficiency values in the right-hand column of the table represent the

Overall efficiency of the rotor/generator system.

$$\eta = \frac{\text{electrical power output from the generator}}{\text{rate of energy input available to the Savonius rotor}} = \left( \frac{I_{\text{total}} R^2 / 746}{\frac{1}{2} \rho A V^3 / 550} \right)$$

where  $\rho$  = density of seawater = 2 slug per cubic foot.

$A$  = frontal area of rotor =  $(2)(11)(16)/144 = 2.44$  sq. ft.

Obviously, the first three efficiencies listed in Table 1 are erroneous, as each exceeds 100 percent. (The remaining two efficiencies are higher than the maximum measured for a Savonius rotor alone in the most extensive series of tests of this type of rotor known to the authors, Ref. 12.1). Further, related RPM data for low values of  $V$  could be valid only if the rotor tip speed exceeded the estimated value of  $V$ , which is manifestly impossible. A discussion of possible sources of these errors is included in the next section.

#### 12.4.1 Possible Sources of Error

Almost all of the measurements in this study were crude, due both to the rushed schedule under which the tests were run and, more importantly, to the insufficient background preparation by the authors. The inconsistency between RPM and estimated velocity  $V$  highlights velocity estimation as a prime candidate for error. Several possibilities for sources of the error exist, and are listed below in order of decreasing predicted impact on the velocity estimate.

1. The floating blocks may have been more influenced by wind and wave action than was the water at the depths (between 1/2 and 3 1/2 feet) at which the rotor operated. The relative rotor-versus-water velocity would thus have been

greater than that between the catamaran and the block. If valid, the error in velocity would be constant.

2. Lateral (rocking) motion of the catamaran would lead to significant lateral motion of the rotor, particularly its lower portions. The omnidirectional nature of the Savonius rotor treats this sideward velocity component like any other component. If valid, this possibility would lead to an underestimate of the true effective velocity by the floating-block approach. The error resulting from this source would tend to decrease as  $V$  increases.
3. If the catamaran were not moving parallel to its length in the following sea, the true effective velocity would exceed the estimate  $V$  by a factor of  $1/\cos \theta$  where  $\theta$  is the angle of divergence.
4. The displacement effect of the catamaran hulls will tend to accelerate the flow around the upper portions of the rotor, again making the estimated velocity too low. For large values of divergence angle  $\theta$ , a further effect may result from vortices shed from the "upstream" hull.

Each of these potential error sources will tend to make the estimated velocity lower than the true value, and thus help explain the observed unrealistically high ratio of rotor tip speed to  $V$ . More importantly, increased values of velocity will tend to reduce the computed efficiency values, via the  $V^3$  term in the denominator of the efficiency relation.

Not all possible "errors" tend to reduce computed efficiency. The authors now appreciate, as they did not at the beginning of the study, that the maximum power can be produced by a Savonius rotor only at a given value of tip speed ratio, and that the maximum power can be produced by an electrical generator only when the impedance of the generator equals that of the load. No attempt to optimize either of these parameters was attempted in this study primarily because the authors were not aware of them in time



to include them. Operation at more nearly optimized values could only improve the overall efficiency of the rotor/generator system.

#### 12.5 CORRECTED RESULTS

The true impact of the error sources listed above cannot be determined without more experiments. It is the authors' opinion that the first source of error is dominant. The high lateral stability of the catamaran and its relatively shallow draft make the second and fourth sources less significant. The third source was neglected by assuming that the divergence angle was small. The resulting error in velocity, arising primarily from the first source, is thus presumed to be roughly constant in magnitude.

After consultation it was decided to assume that, at the lowest velocity examined, the rotor tip speed ratio (equal to rotor tip speed/V) was 0.75. This assumption resulted in a required approximate 1.5 foot per second increase in V compared to that estimated from the floating block approach. Application of this 1.5 foot per second increase for all the previously estimated V values leads to the results of Table II. These results show a gradual reduction in efficiency from a high of roughly 29.5% at 2.5 feet per second to a value of 13.5% at 5.8 feet per second. It is worth noting that, if the second source of error were more significant than was assumed in the calculations for Table 12.2, the results would show considerably less "fall'off" at the higher velocities.

## 12.6 CONCLUSIONS AND RECOMMENDATIONS

Although it has many shortcomings, this study has been successful in demonstrating the suitability of the Savonius rotor in this application, and has identified a number of problem areas and sources of experimental error which were not apparent to the authors at the beginning. It has further demonstrated to them the importance of more adequate theoretical and procedural preparation before experimentation begins.

In any future studies using this apparatus, we recommend:

1. Tests to evaluate the impact of the error sources described above, particularly to evaluate the validity of the 1.5 foot per second "correction" applied to measured velocity.
2. Design a more reliable velocity estimation procedure.
3. Examine experimentally the impact of load variation (via changes in the resistance of the load rheostats) on rotor RPM and power output, and on overall efficiency.

## 12.7 REFERENCE

- 12.1 S. J. Savonius, "The S-Rotor and its Applications", Mechanical Engineering, Vol. LIII, No. 5, pg. 335, May 1931.

Run	t (sec)	V 15/t (ft/sec)	I <sub>total</sub> (amps)	Power Output (watts)	Efficiency (%)
1	15	1.0	0.82	15.4	468
2	7 1/2	2.0	0.10	27.8	104
2a	7	2.15	1.32	40.0	121
3	5	3.0	1.64	61.9	69
4	3 1/2	4.3	1.94	86.5	33

TABLE 12.1   Uncorrected Experimental Results

Run	Corrected V (ft/sec)	Power Output (watts)	Efficiency (%)
1	2.5	15.4	29.5
2	3.5	27.8	19.5
2a	3.65	40.0	24.9
3	4.5	61.9	20.4
4	5.8	86.5	13.5

TABLE 12.2   Experimental Results Including  
a "Correction" of +1.5 Feet  
Per Second in Velocity

### 13. THE FLOATING BREAKWATER

The floating breakwater arrangement was suggested by Dr. Buckminster Fuller who assisted in the design and the funding of this project. Such a breakwater would be useful at Little Spruce Head Island to provide a suitable small boat landing area; it was also a useful project in its own right. A floating breakwater would have certain advantages; it would be deployed in the summer when it is needed, furthermore, it would cause very little environmental change in area compared with a permanent rock breakwater. The task, then, was to design, build and test a floating breakwater.

During the July 1973 Ocean Engineering Summer Laboratory an approximate half scale model of the breakwater was built and tested in Castine Harbor. The concept seemed to work and the decision to design, build and test a full size prototype of the floating breakwater was made. This summer construction and operation of the full scale prototype was attempted.

#### 13.1 DESIGN PRINCIPLES

The breakwater consists of eleven tractor tire innertubes, filled  $3/4$  full with seawater and  $1/4$  full with air, lashed together with polypropylene line, the innertubes being in the vertical position. The innertubes were then lashed to a cover, which envelops the innertubes creating a cylinder 68 feet long by 6 feet in diameter. The innertubes are spaced on 6 foot centers, Figure 13.1.

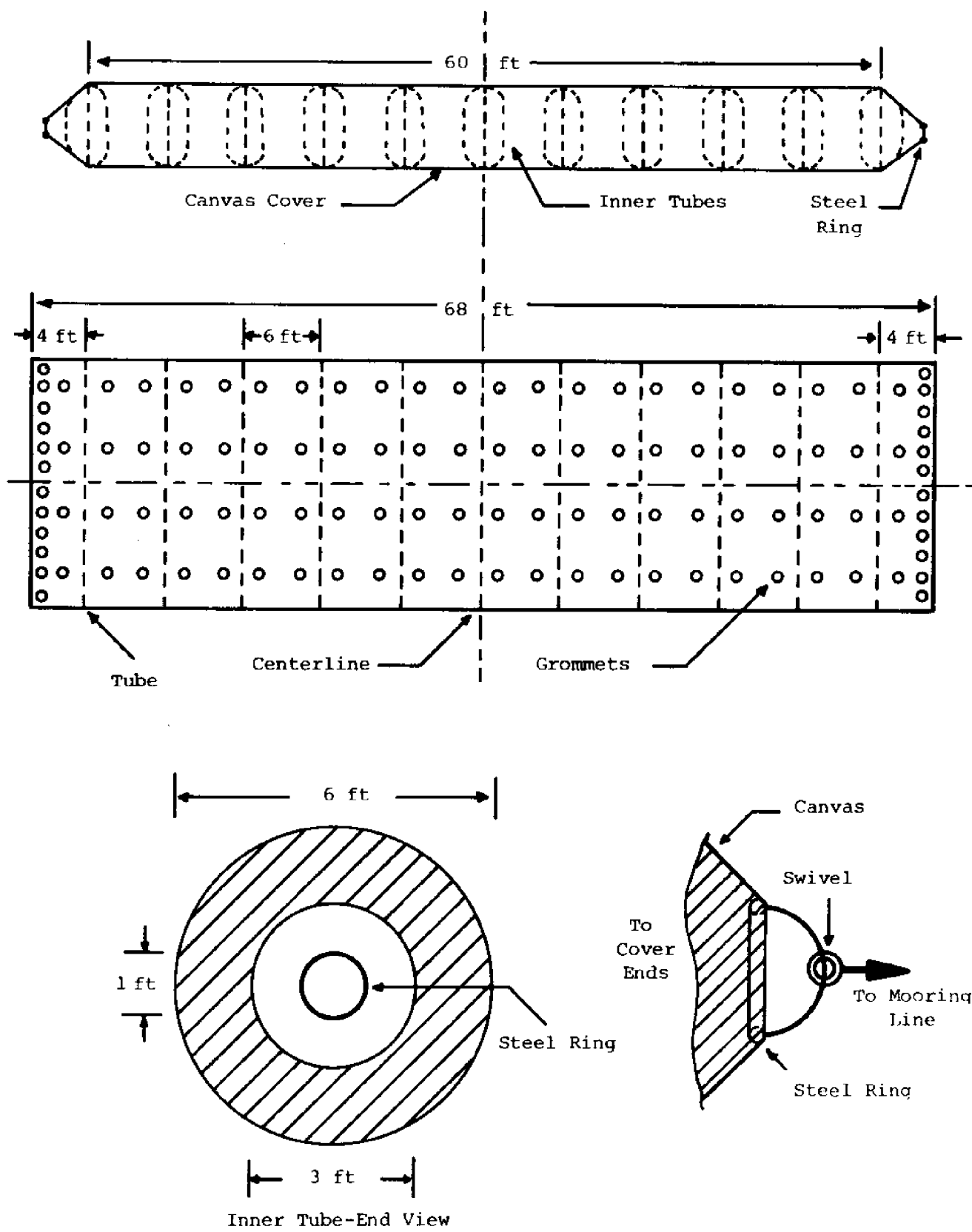


FIGURE 13.1 Floating Breakwater

A local sail-maker constructed the cover of a reinforced plastic material. When it arrived, the grommet holes were laid out, punched and installed. Next the mooring system was designed, necessary materials and anchors procured, the necessary splicing completed and the mooring system assembled.

The mooring consisted of a 25 foot length of chain secured around a rock on shore on one end and a 60 pound Danforth anchor with 40 feet of chain attached on the other end, running over a reef. It was originally planned to embed the anchor in the bottom on the seaward side of the reef with the chain running over the reef, however, the length of chain proved inadequate, and when actually installed, the anchor was placed in a crevice on the reef. A 75 pound mushroom anchor was implanted on either side of the breakwater on the seaward side and an 85 pound Danforth anchor on the leeward side of the breakwater to hold the breakwater in position against the tidal current and wind forces as in Figure 13.2.

#### 13.2 INSTALLATION

The breakwater parts were taken by boat to the island site. The first operation consisted of filling the innertubes with water. Approximately one hour was required to fill each innertube with water because the only available portable pump operated with a low discharge pressure and the tubes have a small fill opening. In the future it is suggested that several tee's be installed on the discharge line with suitable lengths of hose and fittings so that several tubes may be filled simultaneously.

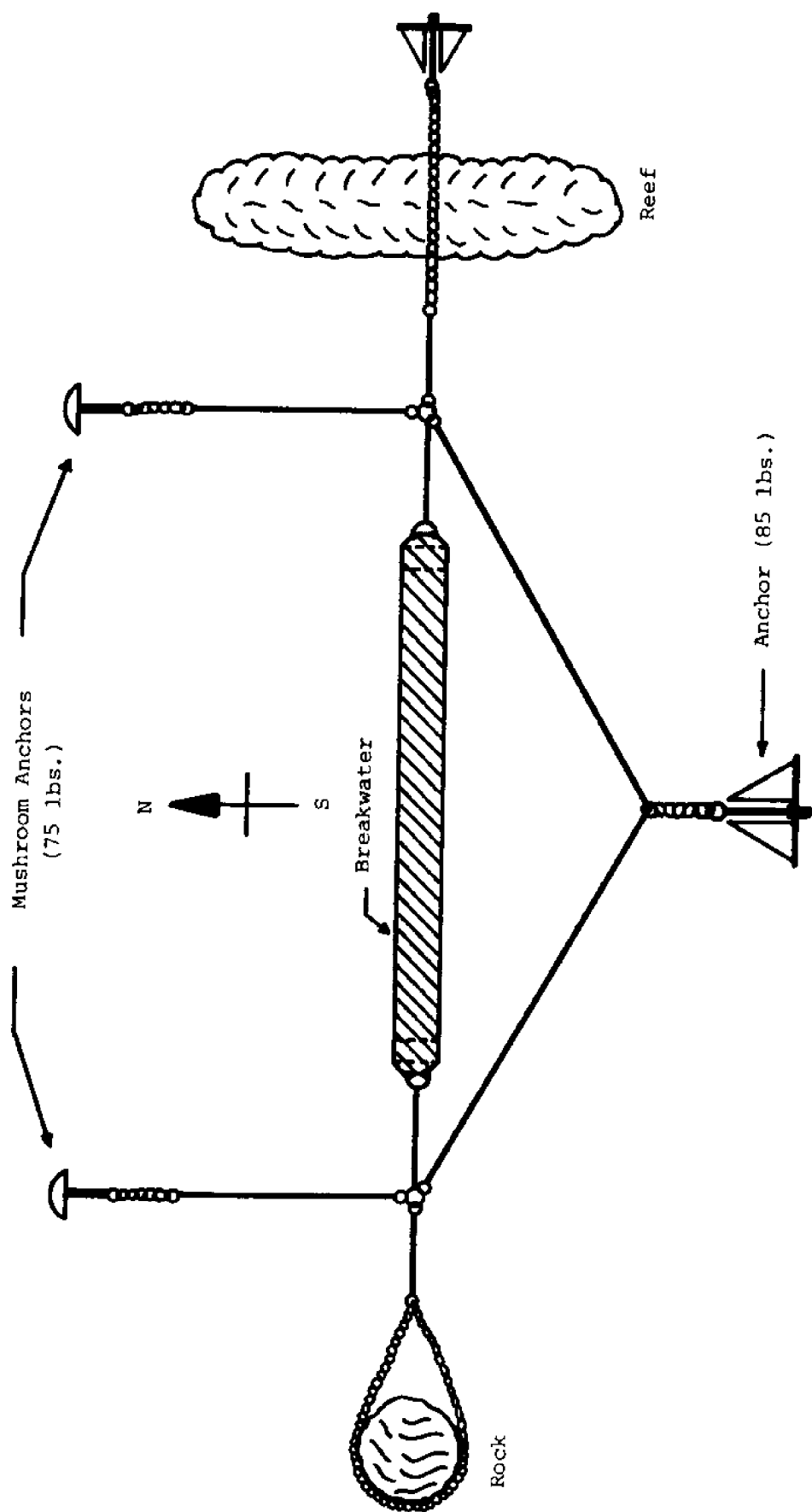


FIGURE 13.2 Floating Breakwater Mooring System

To add the necessary 1/4 air charge to the innertubes, a standard tire air valve was used. This valve was attached via a pipe nipple to the hose of a 2 stage, single hose scuba regulator with the second stage removed to a scuba tank.

The initial preparations and assembly of the breakwater on site were slow and ineffective. The attempt to assemble and install the breakwater was difficult because of the ineffectiveness of divers working in shoulder deep water "wrestling" a 6 foot diameter innertube weighing 500 pounds. When it was attempted to lash the cover to the innertubes, it became obvious that the job was impracticable.

The specific problems are as follows:

1. The innertubes are too awkward (6 foot diameter, 500 pounds) to handle in water.
2. The innertubes are difficult to keep in the vertical position.
3. The innertubes tend to roll in the water and tangle the lines.
4. The cover is heavy and difficult to maneuver (68' x 18', approximately 125 pounds).

Another problem which can be foreseen is the instability of the innertubes in that there are no compression members in the breakwater structure. There is nothing in the breakwater structure to inhibit the tendency of the innertubes to "flop" over into the horizontal position. The only means of resisting this force is by way of the mooring lines, but due to the lack of tensioning of the mooring lines because of the tide range, it is likely that this will not be effective.



### 13.3 CONCLUSIONS AND RECOMMENDATIONS

The installation of the breakwater was not completed due to the problems of assembly of the structure in the water. It is felt that the initial concept and design of the breakwater is feasible. Some modifications in the design to facilitate installation need to be made and a more complete analysis of the installation's mission scenario needs to be made. Students have started work on the next phase of the floating breakwater project, a couple of the proposals for gaining the necessary stability of the structure for installation have been put forth. It is expected that the breakwater will be installed and tested during next summer's Ocean Engineering Summer Laboratory.

#### 14. A PRELIMINARY STUDY OF DIVER PROPULSION USING COMPRESSED AIR

The purpose of this project was to design a propulsion device which would use the energy stored in the compressed air in a SCUBA tank to propel a diver through the water. The main advantage of using compressed air as a power source is that it is normally carried by divers for breathing and the energy it contains is wasted. The use of compressed air as an energy source eliminates the need for extra equipment such as generators which would be needed if batteries were used.

A typical air tank used in SCUBA diving contains seventy-one cubic feet of air compressed to a pressure of 2,250 pounds per square inch. If the tank is discharged at a constant temperature at a depth of eighty feet in water, the amount of energy released is about one quarter horsepower hour or 630,000 foot-pounds. It takes approximately one half hour to breathe this quantity of air at a depth of 80 feet, so the power which is normally wasted while breathing a tank of air at 80 feet is one half horsepower.

To determine the power needed to propel a human being through the water, tests were conducted in the M.I.T. Ship Model Towing Tank. The experiment is described later in this report. The results showed that the drag on a body dressed in diving gear is 9.14 pounds when the velocity through the water is 1.51 knots. Thus, the power needed to maintain this velocity is 0.042 horsepower which is 8.4% of the maximum power that is predicted for an air tank under the conditions discussed above.

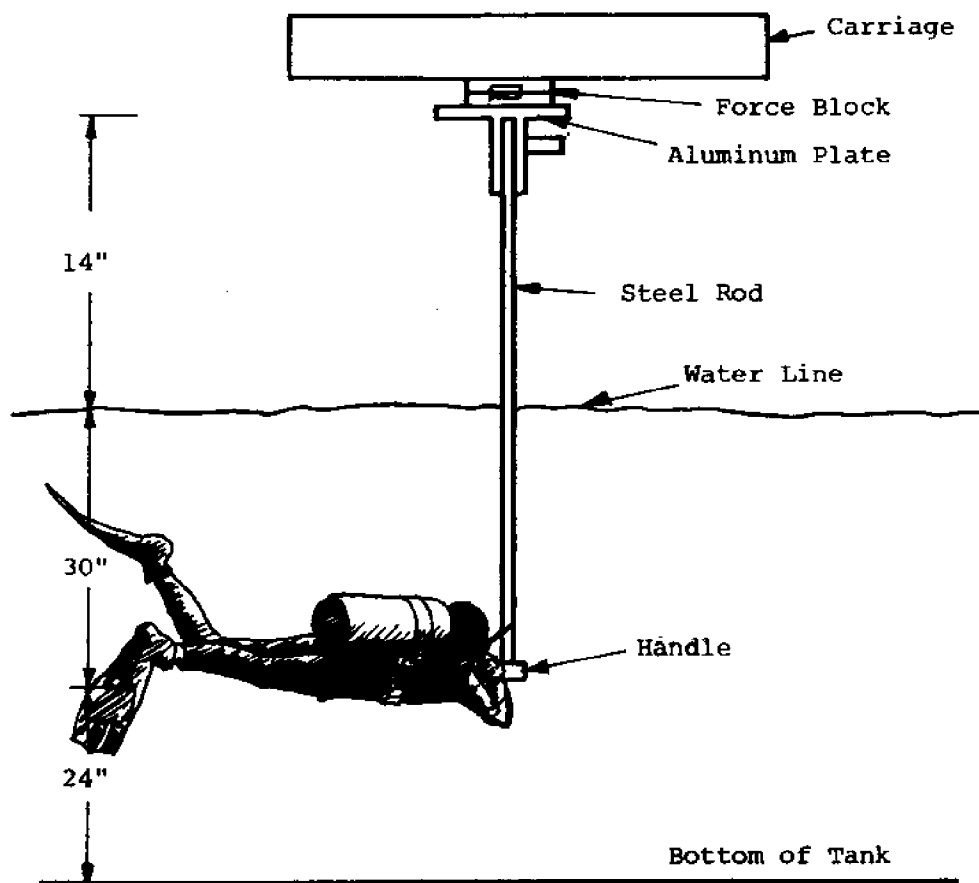


FIGURE 14.1 Apparatus for Drag Measurements

The problem then, was to design an air motor which could be used to drive a water pump, propeller, or some other device which would provide thrust. The motor should make optimal use of the available energy.

#### 14.1 DRAG MEASUREMENTS

##### 14.1.1 Test Apparatus

The apparatus for measuring the drag of a human being dressed in SCUBA gear was arranged as is shown in Figure 14.1. The forward thrust was provided by the carriage and was measured electrically by a force block mounted on its underside. An aluminum plate mounted on the force block held a 44 inch long steel rod. The rod extended 30 inches into the water and was attached to a handle onto which the diver held. The diver was dressed in a wetsuit, hood, face mask, fins, snorkel, air tank, regulator, and 20 pounds of lead weights. The drag was measured using calibrated electrical recording equipment. The tests were first conducted at each towing speed without the diver to determine the drag of the towing arrangement. The diver with full equipment then held on to the towing bar and was pulled along by the carriage without using his flippers. The diver was maintained at a depth of approximately 30 inches. Tests were conducted at five speeds between approximately 0.5 and 1.8 knots.

##### 14.1.2 Experimental Results

The test results at the five towing speeds are presented in table 14.1. The drag results are also presented in the table as  $\text{Drag}/V^2$  in order to determine whether there was appreciable wave drag at the highest speeds. The results suggest that  $\text{Drag}/V^2$  is decreasing at 1.8 knots and thus wave

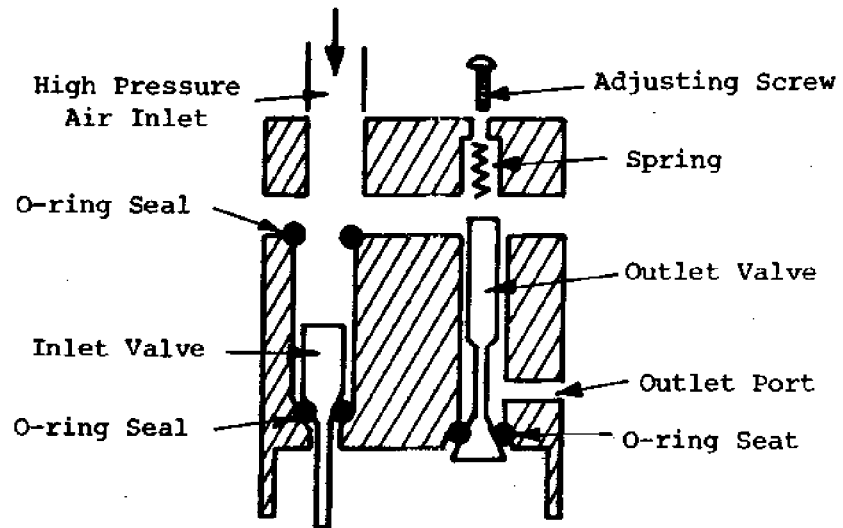
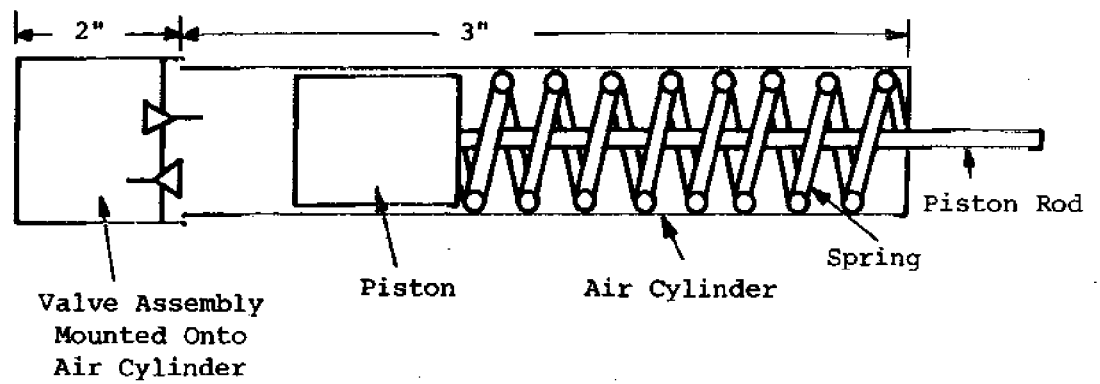


FIGURE 14.2 Air Motor

drag effects must be small. The drag of a fully equipped diver at speeds in the region of 1.8 knots is given approximately by the equation

$$\text{Drag} = 4.0 V^2$$

where V is the velocity in knots.

The tests were conducted in freshwater; the density correction for seawater is within the tolerance of the equation.

#### 14.2 AIR MOTOR DESIGN

Various methods of changing the energy available in compressed air into dive propulsion were considered. These methods include:

1. Direct jet propulsion using air.
2. Propeller driven by air motor.
3. Waterjet using an air motor.

It was concluded that jet propulsion using the air directly was a very inefficient use of the available energy. It was therefore decided that a reciprocating air motor was required to power either a propeller or a waterjet system.

One problem with air motors is the design and construction of a simple valve system. In order to provide an efficient motor the inlet valve cut off should allow the high pressure gas to expand to a lower pressure over a large proportion of the stroke. A piston and valve arrangement was constructed in brass as shown in Figure 14.2. The movement of the pistons opens the inlet valve when the piston approaches the top of the stroke and the air is released when the piston moves down the cylinder and the pressure reaches a value that opens the exhaust valve against the spring. It was intended that the air motor would operate at a constant 500 psi inlet

pressure from a regulator. In the preliminary experiments pressure levels of 50 and 120 psi were used. After some adjustments the reciprocating action could be maintained at both pressure levels in the manner of a pneumatic hammer.

#### 14.3 CONCLUSIONS

The drag of a SCUBA diver has been measured in a towing tank to provide the basis for the design of a diver propulsor. Preliminary experiments were conducted with a simple air motor. The coupling of the reciprocating air motor to a propeller or waterjet unit was not completed.

TABLE 14.1: Drag vs Velocity of a Diver

<u>Velocity</u>	<u>Loaded or Unloaded</u>	<u>Drag, lb</u>	<u>Drag/V<sup>2</sup>, lb/kt<sup>2</sup></u>
0.506 knots	unloaded	0.10	
0.506	loaded	2.23	
0.506	load alone (average)	2.13	8.32
1.006	unloaded	0.40	
1.006	loaded	4.64	
1.006	load alone (average)	4.24	4.19
1.201	unloaded	0.57	
1.201	loaded	7.06	
1.201	loaded	6.74	
1.201	load alone (average)	6.28	4.35
1.510	unloaded	0.97	
1.510	loaded	9.80	
1.510	loaded	10.12	
1.510	loaded	10.68	
1.510	loaded	10.00	
1.510	load alone (average)	9.14	4.01
1.802	unloaded	1.20	
1.802	loaded	13.91	
1.802	loaded	13.20	
1.802	load alone (average)	12.35	3.80



## 15. AN UNDERWATER POWER JACK

A seawater turbine has been incorporated into a hand held diver's power tool that has already been tested successfully as an underwater drill. The goal of the project was to see if the tool could be used as a power supply for other uses, in this case an underwater jack or spreader capable of lifting 500 pounds.

### 15.1 THE SYSTEM DESIGN

Initial power estimates showed that the tool should operate at 1,000 rpm through a 20:1 reduction gear.

The conversion of rotary power to lift would be made using an automotive scissor jack. The design of such jacks is such that they are least efficient when they are completely closed and the efficiency improves as they open. It was determined experimentally that to lift 500 pounds, a torque of 35 foot pounds was required at the jack input shaft when it was in the closed position and the torque dropped to 18 foot pounds for a partially opened position. It was also determined that 20 revolutions of the jack shaft would raise the load one foot.

#### 15.1.1 The Power Tool

The underwater power tool was designed and built earlier and is described in ref. 15.1. It has as the power source an hydraulic turbine using seawater as the working fluid which is supplied from a pump on the surface. The turbine output is controlled by a downstream throttle which is operated by a simple hydraulic valve arrangement placed in the handle of the power tool. The tool had a fiberglass casing around it for protection. This casing was rather bulky and was modified for the jack experiments.

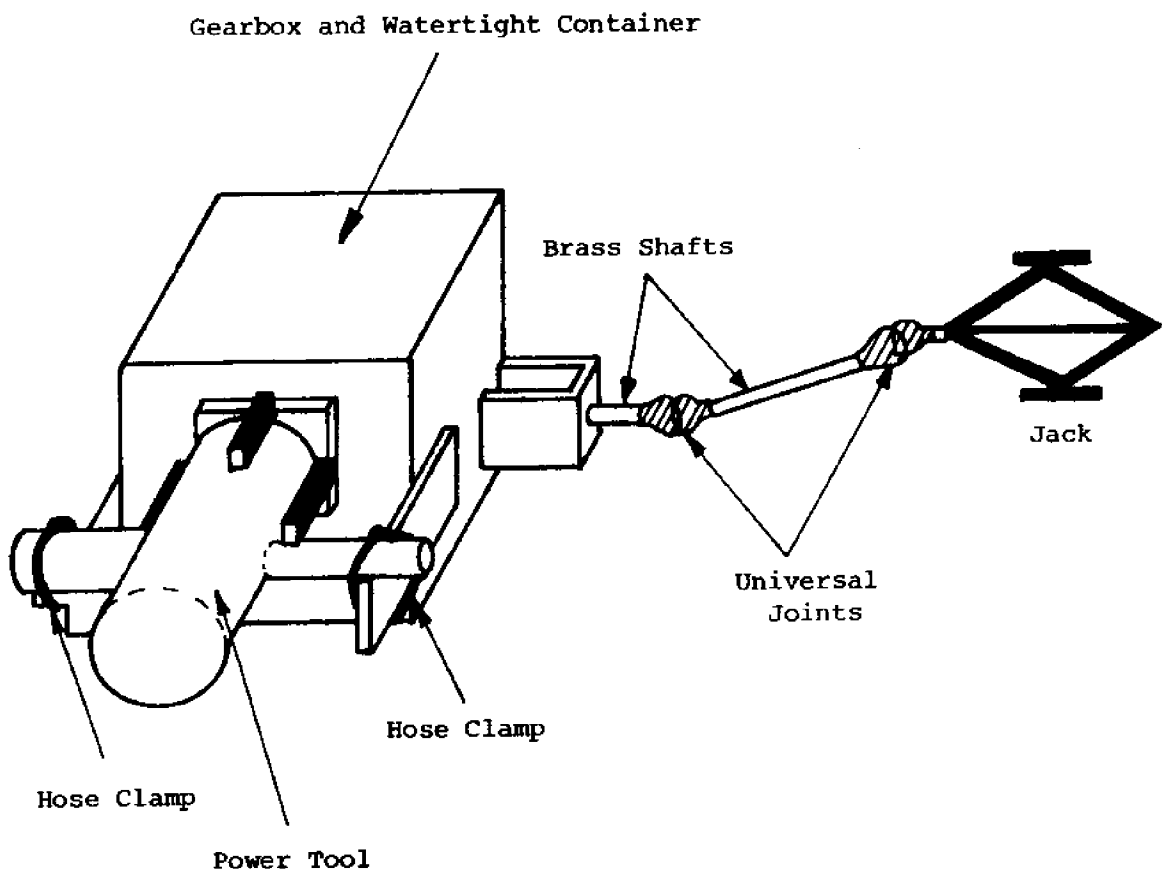


FIGURE 15.1 The Arrangement of the Underwater Jack

#### 15.1.2 The Gearbox and Waterproof Case

The reduction gear selected was an industrial speed reducer with a 20:1 reduction ratio. The external shafts were cut down to about half their original length in order to reduce the size of the waterproof box. Since no PVC tube of sufficient diameter to cover the gear box was available it was decided to fabricate a rectangular PVC box using 3/4 inch thick PVC. Five sides of the box were made watertight by PVC cement while the sixth was screwed down and sealed with an O-ring face seal. The 1/2 inch diameter input shaft and the 1 inch diameter output shaft used dynamic O-ring seals to prevent water leakage. Teflon bearings were cemented to both the inside and outside of the shaft holes to support the input and output shafts. These shafts were turned in brass and joined to the gear box shafts with flexible couplings inside the waterproof box. Arrangements were made to support the power tool at the input shaft and to support the output shaft to the jack, as shown in Figure 15.1.

The output shaft was connected to the jack using two universal joints to allow for relative movement of the jack and the gear box.

#### 15.2 THE EXPERIMENTAL PROGRAM

The power tool, gear box, and jack system were arranged as in Figure 15.1 on the dock at Castine and lifting tests were conducted. Initial attempts at lifting 500 pounds were unsuccessful. The maximum lift attained was about 250 pounds. It was concluded that the throttle system downstream of the hydraulic turbine reduced the torque of the turbine at low speeds.

Experiments were then conducted to measure the stall torque with and without the throttle fitted. The measured stall torques were 10 foot pounds with the throttle in place and 18 foot pounds with the throttle removed. The lifting experiments were repeated with the power tool operating without the throttle. Control of the power tool was maintained by means of a by-pass valve at the centrifugal pump. In these tests the jack was able to lift about 550 pounds.

A test was also conducted underwater with the throttle replaced on the power tool. In this the jacking arrangement was used to bend apart two steel bars which were bolted to a third bar. The main purpose of the test was to determine whether the gear box system was water tight. It was found that a few drops of water entered at the rotating seals.

### 15.3 CONCLUSIONS

An underwater jacking system was constructed using the hydraulic diver power tool. The system as designed was rather cumbersome but was nevertheless capable of being used successfully. The speed of operation was rather high which would make it difficult to control. A larger reduction ratio, say 100:1, would increase the lifting capability and also reduce the speed of operation.

### 15.4 REFERENCES

- 15.1 Ocean Engineering Summer Laboratory, Summer 1974,  
Report No. MITSG 74-12, pp 119-124, February 1974.

## 16. A MANGANESE NODULE MINING DEVICE

The production of successful ocean mining systems requires developments of the various parts of the total system. The nodules must first be found, they must then be collected, concentrated and transported to the surface. At the surface they may be processed or transported to a suitable site for processing. In the 1973 Summer Laboratory the problem of the transportation of the nodules from the bottom to the surface was investigated. The study described here was concerned with collection and concentration of the nodules on the bottom.

Systems now in use have drawbacks which this device would hopefully avoid. The Japanese Bucket system uses a continuous chain of buckets which scours the bottom and brings up buckets of nodules and sea floor. Aside from the amount of waste that must be dumped back into the sea, there is the problem of controlling a chain of buckets that must operate in depths up to 5 miles. Deep Sea Venture has been using a system that employs an air lift and a dredge head. The dredge collects nodules and brings them to the bottom of the air lift. Moving a dredge head on a five mile cable is a difficult job. Directing it is more of a problem.

### 16.1 TECHNICAL DESCRIPTION

After looking at various systems it was decided the device should:

1. Be self propelled.
2. Collect and concentrate nodules at one place
3. Bring up nodulus with a minimum of extraneous material.

At this point several systems for ocean floor transport were proposed. These were an Archimedeian screw drive, transport wheels driven by inflatable bags, and a toothed wheel. The idea of an Archimedeian screw was dropped due to environmental consideration and the inflatable bag wheels would not have had the power necessary. This left the toothed wheel.

The toothed wheel system seemed to have several good points.

1. It was very similar to potato harvesters which do work.
2. The drive wheel and collector unit could be one and the same.
3. Relatively easy to construct for testing.

Work now began on two fronts. First the design of the total system and secondly the design of a system with which we could check the toothed wheel as both a drive unit and a pick up unit.

A small scale model having a one inch diameter toothed wheel design was built. A small motor was attached and the model worked. It would pick small objects out of loose sand.

The large scale model of the Digger (as it was termed) to be tested at the Summer Laboratory was then designed. The construction was largely completed during the month of June 1974. The original design had to be altered due to several design defects. The final design will be described here.

The teeth were made from 1/4" steel rod that was cut to 14", then hand rolled to approximately a 10" radius. These were then cut in

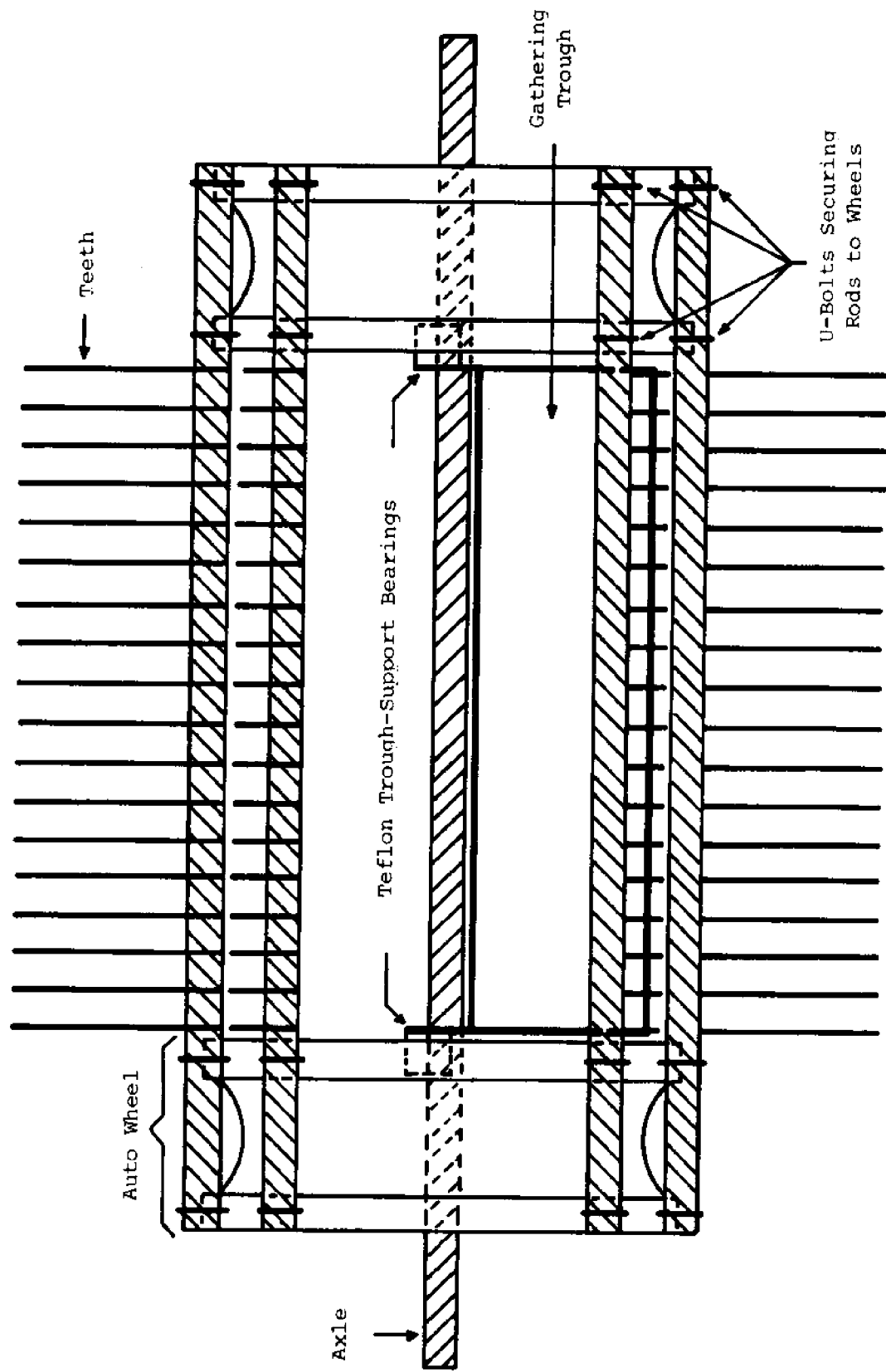


FIGURE 16.1 Arrangement of Nodule Digger

half and welded into 1" diameter steel pipes that were bolted on to two 15" diameter steel auto rims with U bolts so that the angle of attack could be changed. A solid 1" diameter steel rod served as the axle, through which power was to be transmitted. Off this axle swung a steel trough 21" long with a 7" radius to hold the catch. It was mounted on teflon bearings so that it could freely rotate inside the digging drum, as in Figure 16.1.

The device used a gear box working at 20 rpm at a 80 ft. lbs. torque. The gear box was powered by a Saab generator run as a generator. The output of the motor was measured as 1 horsepower at 1,400 rpm. The drive was through a two step reduction to 20 rpm. The gear box was constructed from separate components and housed in a 1/4" thick steel box that was arc welded in order to be water tight. Three O-ring seals were employed. One was used at the end of the motor tube so that there would be access to the motor. One side of the box was sealed to provide access to the gears for alignment. Out of this side there was a rotary seal for the output shaft. In the original design this went to double pulleys and then to the main drive wheel. Due to lack of experience on the designer's part, bending moments were not considered. The large moments caused the belts to lose tension resulting in loss of torque.

During the last week of July it was decided to directly couple the motor to the drum. The universal joint from the underwater power tool was borrowed and adapted to the drum and gear box. To help carry some of the weight of the gear box, extra wheels, which proved useless in the



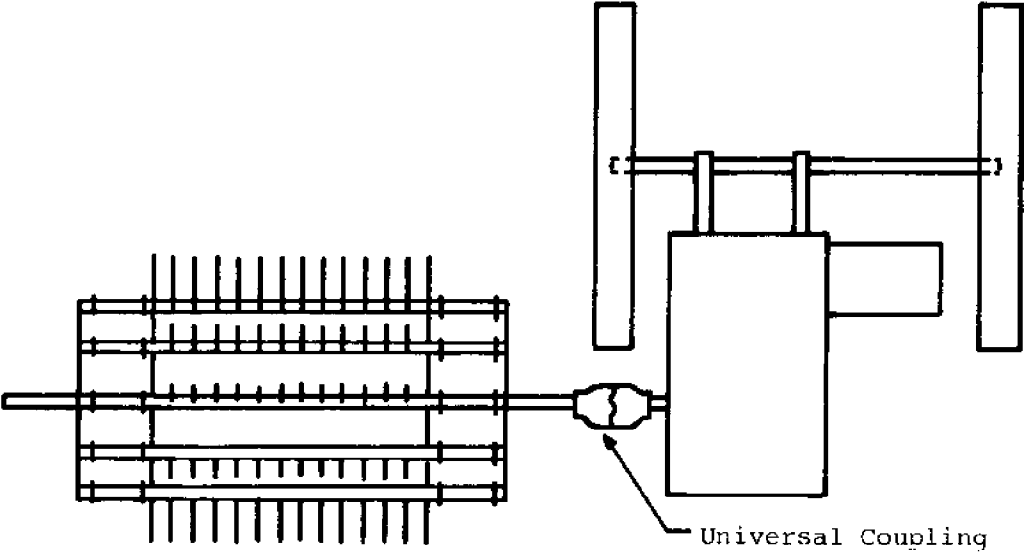
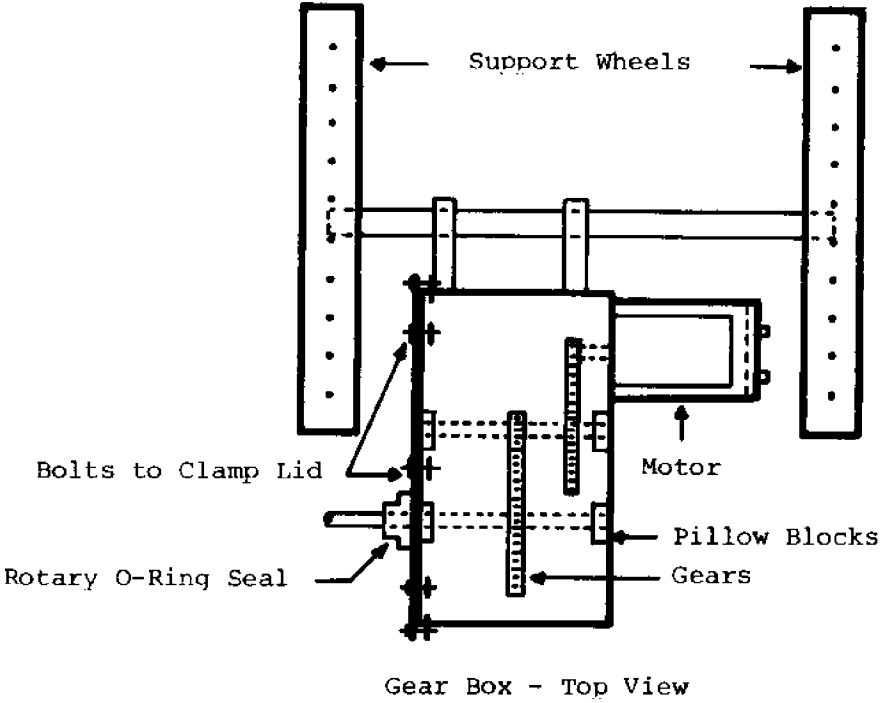


FIGURE 16.2 Nodule Digger and Driver

original design, were now attached to the back of the box. The strut on the front was originally intended to fit on the drum axle. Instead, in our final tests, it was manually supported to keep it out of the sand, as in Figure 16.2.

In the final test the motor would drive the drum if the teeth were not opened beyond 25 degrees. Beyond that the load became too great for the motor. This set-up was run several times.

#### 16.2 EXPERIMENTAL PROGRAM

The Digger was taken down to the beach at low tide. The teeth were aligned perpendicularly to the wheel and tightened. Charcoal briquets, which approximate closely the size of nodules, were strewn in the path of the Digger. These were densely packed and there were 80 to 100 briquets. The Digger was then manually rolled over the briquets at 3 - 5 rpm. The force was applied by pulling up on the teeth from the back of the Digger. On the first pass 3 briquets were picked up. These did fall into the trough as expected. However, the number of briquets was disappointing.

The next step was to see why so few briquets were being picked up. After careful observation it seemed that the pivot point was set up in such a way that the teeth traveled much less than expected through the sand.

The angle of attack was made more acute, to approximately 55 degrees on 3 of the teeth. Again the Digger was run over the briquets. This time it picked up 30 briquets. At this point it was realized that the angle of attack was critical. With this completed, and the realization

that this system really could work, a more detailed plan for experimentation was laid out.

Realizing that angles were important, various angles of attack were tested to see which would be most effective. During the tests it was noted that different downward forces had effect on the percentage of nodules picked up. The tests were carried out on a damp, sandy beach. A 1/4" diameter rod with a 6 lb. force on it was forced approximately 2 1/2" into the sand. The standard course was five feet long and a foot wide with 50 "nodules" in the path of the Digger.

First the Digger was run over the course with an angle of 35 degrees and a total downward force of approximately 150 lbs. It picked up about 20%. When the force was increased to 200 lbs. the take went up to 66% over 5 runs. With the increased force more sand was picked up and loaded into the trough which caused it to tilt. The "nodules" were then closed packed so that they were touching. This time 74% were collected under 150 lbs. pressure.

The angle of attack was changed to 50 degrees. With the load then at 200 lbs., 42% of the nodules were picked up over 3 runs. The load then went to 250 lbs. This time 76% were picked up over 3 runs. However, too much sand was being picked up; this jammed up the machine.

At this point the angle was changed back to 35 degrees. With the 250 lb. load about 70% were picked up.

With the motor providing the drive there would be no load from the top down on the machine. Therefore approximately 20% pick-up was expected. The angle was down to 25 degrees as the motor could not move a

bigger angle due to the higher drag through the sand. The standard test of 50 nodules in 5 ft. was used. In three runs 20%, 20% and 24% were picked up. To make sure the 25 degree angle was not the only reason for the low number of nodules, tests were run with loads of 200 and 250 lbs. The first picked up 48%, the second 54%. This would tend to confirm that 35 degrees was the optimum angle.

Finally, the drive wheel was run in the water. The briquets floated so it was run over a stoney bottom. Two good results were obtained, first it did pick up larger stones and secondly the movement of the water through the teeth got rid of the sand before it got to the trough. This completed the tests.

#### 16.3 CONCLUSIONS

The main objective was to determine if the collecting device was a system that could be developed for Manganese Nodule Mining.

The 15" diameter drum with 6" teeth worked best when the teeth were at an angle of 35 degrees. Increasing the angle at a constant load to 50 degrees reduced the percentage of simulated nodules that were picked up. However, with a load forcing the teeth all the way into the sand, the Digger picked up as much as it did at 35 degrees with the moderate load. Angle and load were a critical combination. More testing should be carried out in the water, where the problem of the trough filling with debris is greatly alleviated.

Motor driven, the device picked up as many nodules as in the unloaded, manually moved drum tests. This proved that the drive wheel could be a pick up wheel as well. This basic concept is simple and it works.

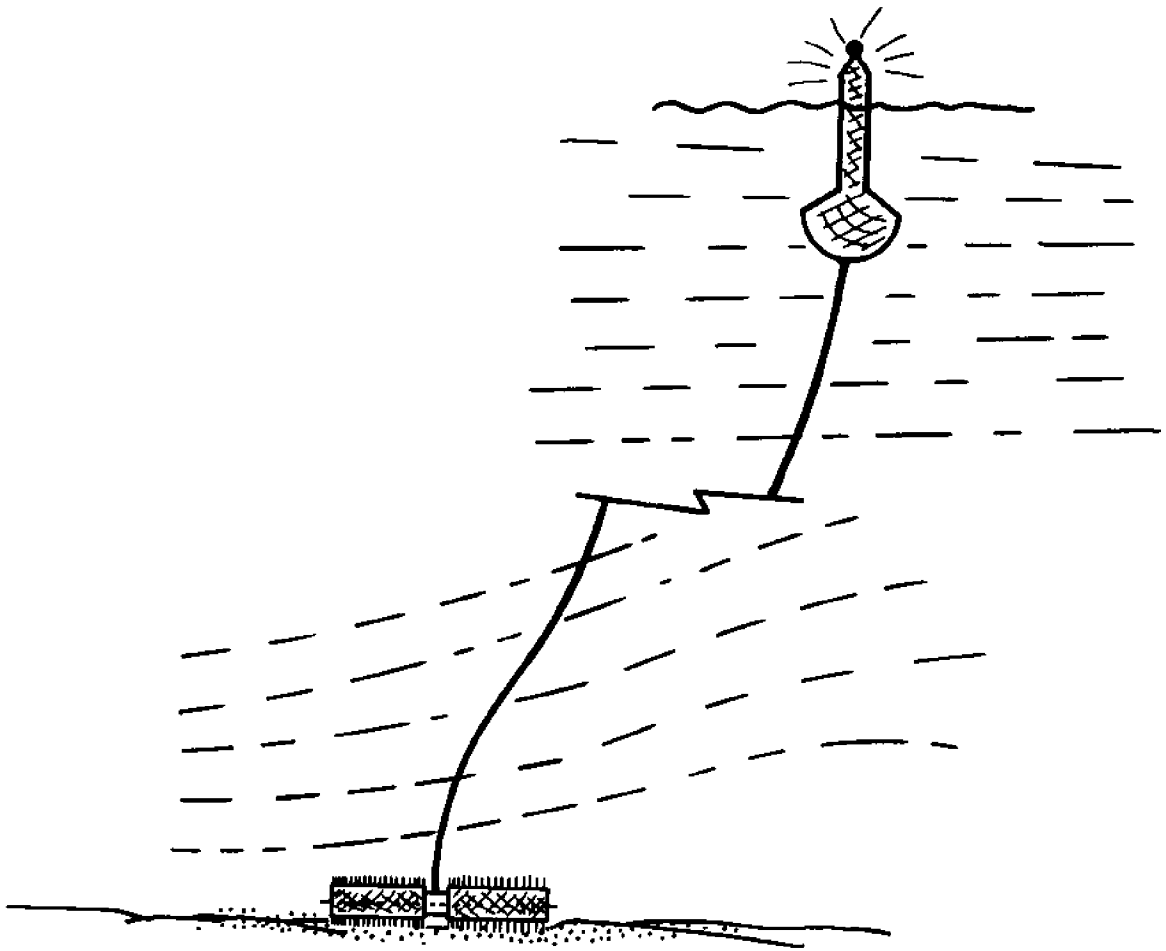
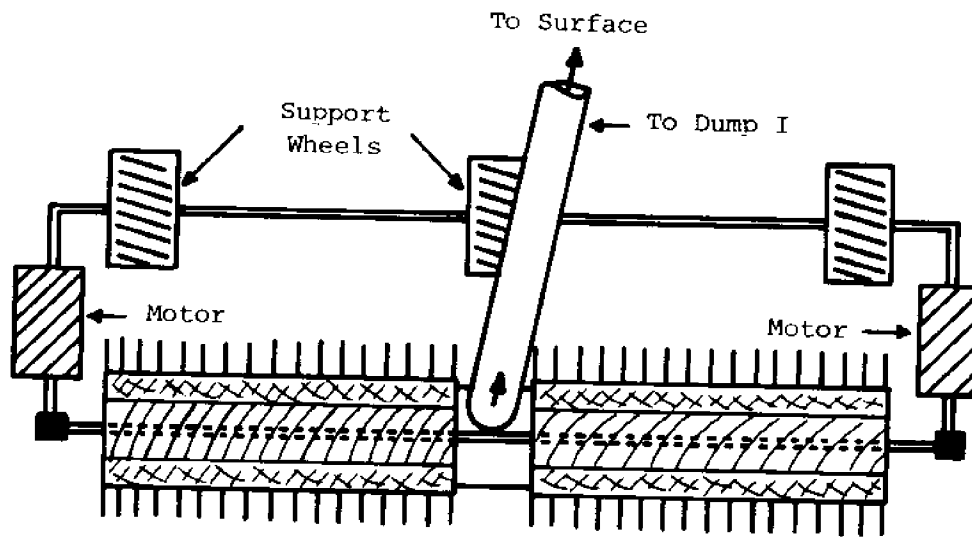


FIGURE 16.2 Future Possibilities of the System

A drive wheel-collector can be made that will work. The best efficiency for the digging drum obtained was 78%. A system could conceivably be developed that would pick up 85% to 90% of the nodules passed over. The system tested was not optimized because available material set the diameter of the drum.

#### 16.3.1 Suggested Integrated System

As presently envisioned the total system would use two of the collector type units, feeding into a central space, as shown in Figure 16.3. The feed would be Archimedean screws fixed on the axles that pull the nodules to the center. From the center a suction lift system would bring the nodules to the surface. The two drive drums would be independent of each other. This would make it possible to steer the device over the sea floor.

## 17. UNDERWATER ARCHEOLOGICAL WORK ON THE "DEFENCE"

### 17.1 INTRODUCTION

During the 1974 Summer Laboratory the wreck sites of the "Defence", a Revolutionary War privateer and the "Alice E. Clark", a four-masted coal schooner sunk in 1909 were further explored. The "Defence" was the center of study while the wreck site of the "Alice E. Clark" served as a diver training location and a testing area for "Snoopy", the remote controlled underwater visual reconnaissance vehicle discussed below.

The primary objective of this year's diving effort in the "Defence" was to construct a grid-coordinate system by which a complete survey of the ship's remains could be studied. This system consisted of yellow polypropylene line laid off around the wreck's perimeter, along the centerline and athwartships across the ship at measured intervals. Substantial objects found at the wreck site could then be plotted in relation to the grid system on the wreckage by the surface mapping crew. (See the map of the wreck site).

The following is a day-by-day account of the work carried out by the dive teams visiting the wrecks of the "Alice E. Clark" and the "Defence".

#### Friday - 5 July 1974

The "Defence" was located on side scan sonar in Stockton Springs Harbor. Buoys placed aft on the wreck and forward near the cook stove. Main and after mast steppings were located.

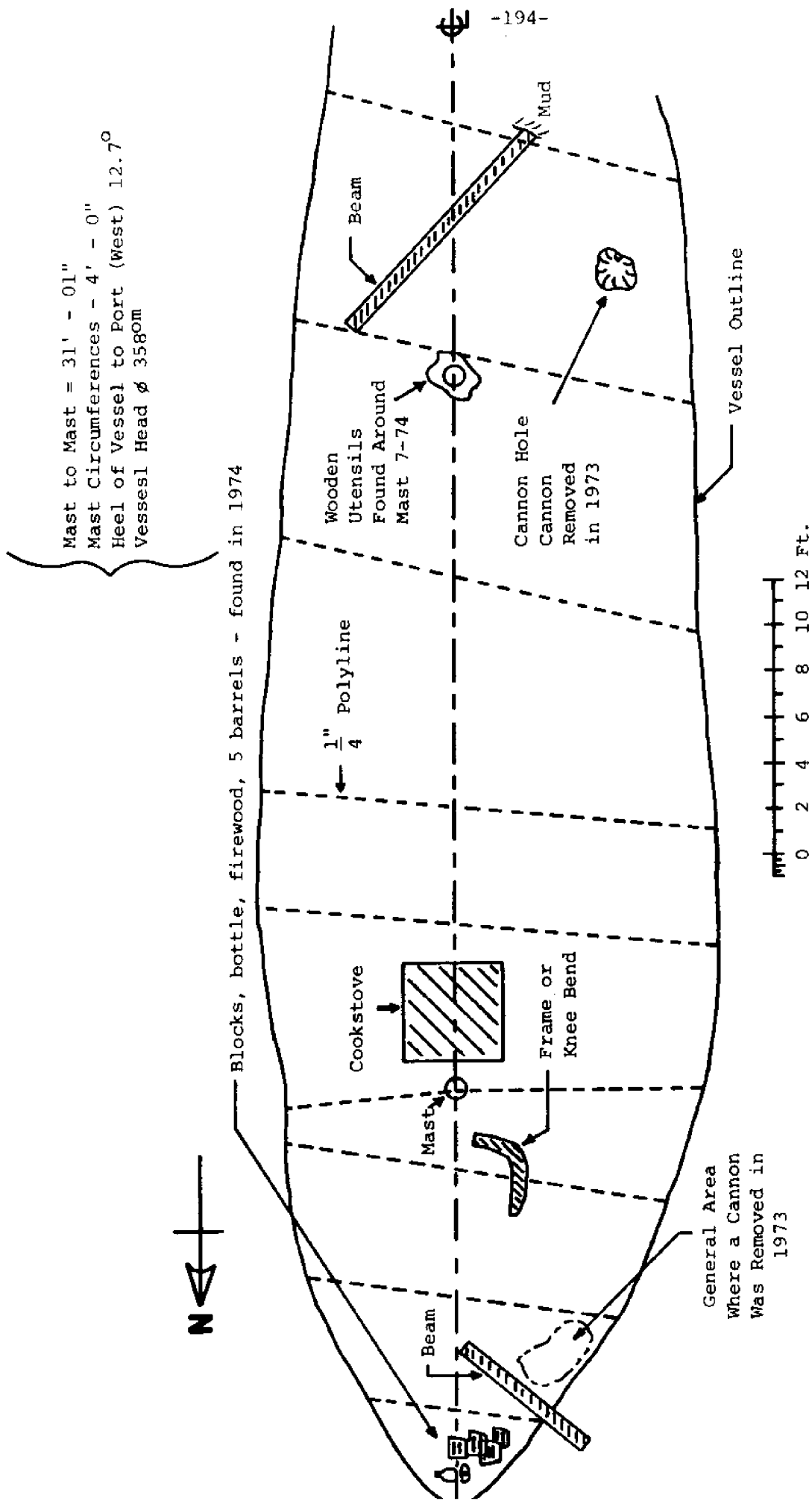


FIGURE 17.1 The Survey of the Wreck of the "Defence"



Saturday - 6 July 1974

A mooring was secured to a timber located back aft on the "Defence". This day was primarily an orientation dive for new divers. The bow's perimeter was excavated briefly. A beef barrel, cannon balls and other unknown artifacts were located near the cook's stove.

Monday - 8 July 1974

In initiating a type of line grid system on the wreck for reference, a line was arranged athwartships from the mainmast to both sides of the hull. Another line was run perpendicular to the first, from the mainmast to the stem. Measurements seemed to suggest that the ship lay on a list to port (west). After more measurements frames were counted along the port side.

Tuesday - 9 July 1974

The ship's sides were outlined by nailing polyproline from rib to rib extending from the stem aft as far as the ribs could still be found. The bow area was again explored, this time inboard of the stem. More scattered timbers were located and plotted.

Wednesday - 10 July 1974

A wooden beam, approximately 6" x 8" was located about three quarters of the distance aft on the starboard side. The aftermast was located and after digging about its base, small wooden utensils were found. A new line was strung along the supposed centerline, from the mainmast to the aftermast. More grid lines

were placed athwartships at five foot intervals extending aft 30 feet from the stem. A 48" aftermast circumference was recorded, transverse lines were checked.

Thursday - 11 July 1974

With good visibility, black and white photographs were taken at various points on the wreck. More digging about the stem turned up a very well preserved double block with one shive missing. The area of excavation was suspected to be the bos'n locker. More cannon balls were found just forward of the aftermast, one weighing about a pound, the other of the same size, weighing almost six pounds. Frame spacing forward and aft was checked.

Saturday - 12 July 1974

Test operations were run on the "Defence" site with "Snoopy", a remote controlled, self-propelled reconnaissance submersible carrying a television camera and an 8 mm movie camera. Television signals were displayed on a screen connected by cable to the camera. It was demonstrated by two representatives from the Naval Underseas Center. More observations were then made on the "Alice E. Clark".

Monday - 15 July 1974

More test runs for "Snoopy" on the "Defence" site. A previously discovered tackle block was brought up for inspection by Ed Churchill of the State Museum and Edward Palmer of the Searsport Museum. A short pine log, evidently cut with an axe

was recovered and brought up. The framework was again inspected and athwartship measurements were taken between frames. Threatening skies aborted the dive and we returned to Castine.

Tuesday - 16 July 1974

Grid lines were drawn taut and more measurements taken from: mainmast to aftermast, center line athwartships to either side, athwartship line longitudinal to the next athwartship line. Again there was evidence of the ship's heel to port. The cookstove's angle was measured.

Wednesday - 17 July 1974

More pictures were taken, this time in color. Grid lines were secured athwartships from 40' aft at 10' intervals. More athwartship measurements were recorded.

Thursday - 18 July 1974

The day was devoted to an observation dive on the "Alice E. Clark". A large "Bull Gear" was located aft, as was the ship's wheel. The after portion of the hull was still pretty well intact. Clear diving even to fifty foot depths.

Monday - 22 July 1974

More measurements were taken on the stem of the "Defence". With the grid lines now in place, surveying was done and substantial surface objects were plotted with respect to their location on the wreck. More digging around the fore peak area to define the location of the stem turned up various size tackle blocks, belaying pins, various pieces of oak, granite, flint, one dark glass bottle still

intact, bones from a meat barrel and the broken top of a barrel. All was returned to the wreck after their inspection.

Tuesday - 23 July 1974

Dimensions in the athwartship direction were taken along after grid lines. The remaining squares were surveyed and plotted out. Two barrels were located and inspected in the forward area already exposed. They appeared to have rope hoops instead of metal. The keel, under the barrel, was measured. A broken mug, some rope, a metal strap and bone were found in the search of the keel.

Thursday - 25 July 1974

The final dive on the "Defence" for the summer lab session was conducted. The main objectives for this dive were to recover previously found artifacts for preservation by the Maine State Museum and a more detailed study of the cookstove was made. The measurements from the foremast to the mainmast were made again along with the transverse grid lines between the two masts. The buoy markers were removed from the wreck.

## APPENDIX I

### SCUBA DIVING STANDARD OPERATING PROCEDURES

The purpose of this instruction is to establish responsibilities and standard operating procedures for SCUBA diving operations conducted in conjunction with the 1974 MIT-MMA Summer Laboratory at Castine, Maine.

#### Diver Quals

Only divers certified by formal SCUBA courses such as NAUI, YMCA or U.S. Navy Diving School will dive in this program.

#### Diver Instructions

1. No recompression diving will be conducted.
2. A safety diver will be fully rigged and standing by whenever divers are in the water.
3. All divers will wear the inflatable flotation vest.
4. Divers will maintain visual contact with their assigned buddy. As soon as visual contact is lost, a diver will surface.
5. Depth limit is 45 ft. for newly qualified divers until further open water checkout by the diving officer.
6. All divers shall report to the Diving Officer before entering the water and notify him of any dives conducted within the last 12 hours.

#### Operating Procedures

1. The Diving Officer shall:
  - a. Give the diver briefing.
  - b. Maintain station in the dive launch.
  - c. Assign buddy teams.
  - d. Designate safety diver.

- e. Make equipment check of divers prior to their entering the water.
- f. Maintain the diving log and repetitive dive sheets.
- g. Direct chase boat activities.
- h. Ensure diving flag is visible.
- i. The diving officer may delegate temporary responsibility to the assistant diving officer when he is actually diving.

2. The Diving Officer shall have the final determination with regard to diving conditions and diver capabilities for a given dive.

3. The safety diver shall be prepared to render aid at the discretion of the diving officer to any disabled diver. He shall be rigged prior to any diver entering the water.

4. Diving ops. will normally be conducted from the PANTHALASS.

5. The MMA Medical Officer (Dr. Russell) shall be informed when open water dives are planned and suitable communication procedures established in the event of emergency.

6. All dive gear shall be off-loaded as soon as the boat returns to port. Gear shall be washed in fresh water and stored in a designated place. Tanks shall be filled as soon as possible by personnel qualified on the air compressor.

#### Emergency Procedures

In any emergency the Camden Marine Operator may be utilized to conduct telephone calls from the boats. In case of air embolism or decompression sickness the nearest recompression facility is at Portsmouth

Naval Shipyard. Emergency medical evacuation is made by helicopter; the following steps are to be followed:

1. Call Coast Guard on VHF channel 16 and request emergency medical evacuation. Identify yourself as M.I.T.-Maine Maritime Diving Group. Give victim status and location.
2. If the return trip by boat to Castine will involve some time call MMA via Camden Marine Operator.
3. Personnel at MMA will call the Duty Officer at Portsmouth, 207-439-1000, Ext. 1900. Tell him that victim is on the way for recompression.
4. Administer first aid in accordance with App. A of the U.S. Navy Diving Manual until arrival of a medical doctor qualified in diving medicine. Air embolism and decompression sickness treatment is in section 1.6.2-1.63 of USNDM.

the clock on the teletype/paper tape reader side of the interface makes the paper tape reader look to the computer like a very fast teletype, and thus completely compatible. Light emitting diode to phototransistor coupling is used to provide a method of communicating with the computer while keeping it waterproof.

The most important component in this interface is a Universal Asynchronous Receiver-Transmitter integrated circuit (UART). Given a pulse of the send character line, it sends the 8 bits on the computer bus out in a serial fashion on the transmit line at one-sixteenth the clock rate. The receive section of the UART recognizes a start bit from the teletype/papertape reader, changes the subsequent 8 bits of serial data to a parallel form (8 separate lines), and puts the data available line high. A read request signal will put this data onto the computer bus and reset the data available line.

The UART draws considerable power, (60 ma at 10 v and 10 ma at -12v). It is not operational when the submarine is in the water, so power control circuitry is used which supplies power to the UART only when clock pulses are coming in.

The reader relay line allows the computer to request one character at a time from the slow paper tape reader attached to the teletype. When the line is pulled high it sends a single pulse to the reader relay, which should cause the reader to send one character. The reader sends one character most of the time, but occasionally sends two, three, or more when given a single pulse.